Wheat Dough Characterisation at Industrial Bakeries

Jødal, Anne-Sophie Schou

DOI (link to publication from Publisher):
10.5278/vbn.phd.eng.00079

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

WHEAT DOUGH CHARACTERISATION AT INDUSTRIAL BAKERIES

BY
ANNE-SOPHIE SCHOU JØDAL

DISSERTATION SUBMITTED 2021

AALBORG UNIVERSITY
DENMARK

WHEAT DOUGH CHARACTERISATION AT INDUSTRIAL BAKERIES

by

Anne-Sophie Schou Jødal

AALBORG UNIVERSITY
DENMARK

Dissertation submitted 2021

.

Dissertation submitted:	January 2021
PhD supervisors:	Professor MSO Kim Lambertsen Larsen, Aalborg University, Denmark Jeppe Møller Lorentzen, Cluster Operations Excellence Manager, Lantmännen Unibake Denmark
Assistant PhD supervisors:	Associate Professor Thomas Ditlev Brunø, Aalborg University, Denmark Associate Professor Kjeld Nielsen, Aalborg University, Denmark
PhD committee:	Associate Professor, Morten Lykkegaard Christensen (chair) Aalborg University Scientific Manager, Merete Møller Engelsen Novozymes A/S Docent Tuula Sontag-Strohm University of Helsinki
PhD Series:	Faculty of Engineering and Science, Aalborg University
Department:	Department of Chemistry and Bioscience

ISSN (online): 2446-1636
ISBN (online): 978-87-7210-870-4

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2021

ENGLISH SUMMARY

Bakery products made from wheat flour are popular food products all over the world. Lantmännen Unibake Denmark manufactures bakery products, such as bread and Danish pastry. While many production processes are automated in the industrial manufacturing of bakery products, product development and adjustments of the production processes are to some extent characterised by a craft approach. Much research has been conducted within cereal science, but this knowledge has so far to not been fully utilised in the baking industry. There is an increasing demand in the market today for more product varieties, which entail smaller batch sizes, shorter product life cycles and shorter time to market. Before high-variety production of Danish pastry can be obtained with sufficient efficiency, the present manufacturing system faces various challenges, which must be handled. The business strategy mass customisation addresses how manufacturing of individualised products at low cost can be obtained. It was found that to adopt mass customisation in the Danish pastry manufacturing, multiple challenges had to be addresses, including a requirement of more knowledge of the relations between the raw materials, the production processes and the final product, as well as more measurements of relevant dough properties, data collection and data analysis must be conducted in industry.

The viscoelastic properties of wheat dough are determining for the processability and the resulting product quality. Dough analysis was performed using the alveograph method, in which biaxial extensional properties are measured by inflating a dough bubble. For every analysis, ten parameters are extracted from the resultant pressure-time curve or derivatives of it. The linear correlation coefficients between the ten parameters were determined. Four parameters were almost perfectly correlated ($r \geq 0.97$) with other parameters, and they therefore did not provide much additional information. Less strong correlations could also be observed between other parameters, which might be explained by interlinks between them.

The alveograph method is normally used for flour analysis, and a protocol for alveograph analysis of full formula dough was therefore developed. The analysed full formula dough was either made by adding the ingredients to the alveograph mixer or taken as dough samples from the industrial production. The dough temperature was lowered compared to the standard protocol to limit the yeast activity. It was observed that the mixing time had a larger effect on the parameter values for the full formula dough analysed by the adjusted protocol compared to flour-water dough analysed by the standard protocol. One general mixing time could therefore not be found for full formula dough but must instead be determined for each dough type. The effects of different flour qualities for the properties of different dough types, including simple flour-water dough as well as two doughs with all ingredients for bread and Danish pastry, were also assessed by the adjusted alveograph protocol. Rankings and significant differences of the parameters between the flour types were different for the

three dough types, indicating that the effects of the ingredients are dependent on the flour properties. A range of dough samples from the industrial Danish pastry production were also analysed by the adjusted alveograph protocol. It was found that the protocol could differentiate between doughs with differences in the dough recipe, while other variables, such as addition of pastry trimmings, could not be detected. Other analysis methods might therefore be needed to evaluate the effects of these variables.

The adjusted alveograph protocol can be used to analyse full formula dough. This exemplifies that established analysis methods can be adapted for analysis of industrial process variables. This will be an important step towards a more knowledge-based and data-driven development in the industrial manufacturing of bakery products, which is a prerequisite for an efficient high-variety production.

DANSK RESUME

Bagværk lavet af hvedemel er populære fødevarer i hele verden. Lantmännen Unibake Danmark fremstiller forskelligt bagværk, bl.a. brød og wienerbrød. Mange produktionsprocesser er automatiserede ved den industrielle fremstilling af bagværk, mens produktudvikling og justeringer af produktionsprocesserne er i nogen grad præget af en håndværkstilgang. Der er lavet meget forskning i cerealier, men denne viden er endnu ikke blevet udnyttet til fulde i bageindustrien. I dag er der en stigende efterspørgsel efter flere produktvarianter, hvilket indebærer mindre batch-størrelser, kortere produktlivscyklusser og kortere *time to market*. Før wienerbrød kan produceres i mange varianter med tilstrækkelig effektivitet industrielt, må en række udfordringer i det nuværende produktionssystem først håndteres. Forretningsstrategien *mass customisation* adresserer, hvordan fremstilling af individualiserede produkter med lave produktionsomkostninger kan opnås. Det blev fundet, at for at gå over til *mass customisation* i den industrielle fremstilling af wienerbrød er det nødvendigt, at der opnås større viden om relationerne mellem råvarer, produktionsprocesser og det færdige produkt, samt at der udføres flere målinger af relevante dejegenskaber, dataopsamling og dataanalyse i industrien.

Hvededejs viskoelastiske egenskaber er afgørende for dejens bearbejdelighed og kvaliteten af produktet. Alveografmetoden blev anvendt til at analysere dej, hvorved de biaksiale ekstensionale egenskaber blev målt ved at blæse en boble af dej. For hver analyse udtrækkes ti parametre fra den fremkomne tryk-tid-kurve eller afledte af denne kurve. Den lineære korrelationskoefficient mellem de ti parametre blev fundet. Fire af parametrene var næsten perfekt korrelerede ($r \geq 0.97$) med andre parametre, og disse indeholdt derfor ikke meget yderligere information. Mindre stærke korrelationer blev også observeret mellem nogle af de andre parametre, hvilket kan skyldes deres indbyrdes afhængighed.

Alveografmetoden anvendes normalt til melanalyser, og der blev derfor udviklet en protokol for alveografanalyse af deje med alle ingredienser som eksempelvis brøddej eller wienerbrødsdej indeholder. Den analyserede dej var enten lavet ved at tilsætte alle ingredienserne til alveografmixeren eller taget som dejprøver fra den industrielle produktion. Dejtemperaturen blev sænket ift. standardprotokollen for at mindske gæraktiviteten. Det blev observeret, at æltetiden havde en større effekt på parameterværdierne for dejene, hvor alle ingredienser var tilsat, analyseret med den tilpassede protokol sammenlignet med mel-vand-dej analyseret med standardprotokollen. En generel æltetid kunne derfor ikke fastsættes for dejene med alle ingredienser, men måtte i stedet bestemmes for hver dejtype. Effekten af forskellige melkvaliteter for egenskaberne af forskellige dejtyper, inklusiv simpel mel-vand-dej og to deje med alle ingredienser til henholdsvis brød og wienerbrød, blev også undersøgt ved brug af alveografanalyse. Rangering og signifikante forskelle af parametrene mellem meltyperne varierede mellem de tre dejtyper, hvilket

indikerede, at effekten af ingredienserne til dels var afhængige af melegenskaberne. En række dejprøver fra den industrielle wienerbrødsproduktion blev også analyseret med den tilpassede alveografprotokol. Det blev observeret, at protokollen kunne differentiere mellem deje med mindre forskelle i opskriften, men andre variable f.eks. tilsætning af kantdej ikke kunne detekteres, og andre analysemetoder kan derfor være nødvendige for at undersøge effekten af disse variable.

Den tilpassede alveografprotokol kan bruges til at analysere deje med alle de ingredienser, som forskellige typer af bagværk normalvis indeholder. Dette eksemplificerer, at etablerede analysemetoder kan tilpasses til at analysere industrielle procesvariable. Dette vil være et vigtigt skridt i retning af en mere vidensbaseret og datadrevet udvikling i den industrielle fremstilling af bagværk, hvilket er en forudsætning for en effektiv produktion af mange varianter.

ACKNOWLEDGEMENTS

I would like to acknowledge Innovation Fund Denmark (grant 5189-00062B) for supporting my studies.

I would like to thank my supervisor Kim Lambertsen Larsen, who made this PhD possible for me. Without his guidance and involvement in my work the last years, I could not have finished this project. Thank you for the many long and valuable discussions and for all your help and support.

I would also like to thank Jeppe Møller Lorentzen at Lantmännen Unibake Denmark for his help and encouragement. I have enjoyed the many talks and walks in Hatting and around the factory. Thank you for reminding me to focus on what I can change.

I would further like to say thank you to my co-supervisors Thomas Ditlev Brunø and Kjeld Nielsen for guidance and discussions, as well as for introducing me to other aspects of science than what I am used to.

Acknowledgement goes to Birthe P. Møller Jespersen, Tomasz Pawel Czaja, Franciscus Winfried J. van der Berg and Lisbeth Dahl at University of Copenhagen for a pleasant collaboration and external stay. Thanks for enlightening discussions and for giving me the possibility to work together with you.

I would like to thank present and former members of the Section of Chemistry at Aalborg University for upholding a pleasant working environment. A special thank goes to the “lunch club” for the enjoyable company and the many work and non-work related discussions. I would also like to acknowledge present and former members of the Mass Customization group at Department of Materials and Production at Aalborg University for always providing good company. Further, I would like to thank all employees at Lantmännen Unibake Denmark in Hatting, both in the administration and in the production, for making me feel welcome, being open-minded and helping me. Many thanks go to Sofie Bech for fellowship and collaboration. Thank you for the many talks in the car, the multiple discussions and for broadening my horizon.

Last but not least, I would like to thank my family and friends for being who you are. I would like to acknowledge my uncle-in-law Lars for help with grammar check of the thesis. Special thanks to my parents Svend and Lone, my brother Johan, my sister Caroline and my friend Lisbeth for the support they have given me. Thanks to my son Jonathan for great smiles and reminding me what matters most. My husband Christian must have the greatest thanks for all the technical support, including fixing my R scripts and figures, as well as always believing in me and for all his patience, encouragement and understanding throughout this period.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

Bakery products, such as bread, cakes, pastries and biscuits, are popular food products and can be found in many variants worldwide (W. P. Edwards, 2007). Especially bread is very widespread and produced in countless varieties over the world. Bread has been known for several thousand years and is considered to be one of the oldest processed food (Cauvain, 2015; Goesaert et al., 2005). Because of their widespread consumption, the market for bakery products is relatively large. Bakery products are often made from wheat flour, although other cereals may also be used. Wheat has unique properties, as it can be used to form a viscoelastic dough with gas-holding capacity resulting in a relatively stable porous bread after baking (Goesaert et al., 2005).

Bakery products can be made at home, at small craft bakeries and at industrial plant bakeries. Lantmännen Unibake is one of Europe’s largest bakery groups producing bread, cakes and pastry at 36 bakeries in 16 countries and supplying to more than 60 international markets (Lantmännen Unibake, 2019). This includes Denmark, where Lantmännen Unibake has several bakeries. Many of the bakeries are characterised by high-volume manufacturing of bakery products. This has for some of the bakeries resulted in a manufacturing system with long changeover times between different products, long ramp-up times as well as large waste of materials (Bech, Brunoe, Nielsen, et al., 2019). The market today demands larger product variety and individualised products (Koren, 2010; Y. Wang et al., 2017). In the bakery industry, this has resulted in higher introduction rates of new products and ingredients, smaller batch sizes and shorter product life cycles (Bech, Brunoe, Nielsen, et al., 2019). Several aspects of the manufacturing must be improved to achieve a production system suited for production of high-variety manufacturing (Bech, Brunoe, Nielsen, et al., 2019). Some of the aspects, which require further research and development, are control and optimisation of raw materials and production processes (Bech, Brunoe, Nielsen, et al., 2019; Li Vigni et al., 2009; Ulrici et al., 2008).

Bakery products cover a wide range of different product categories. Many of the bakery products share some of the same ingredients, including wheat flour and water, and the production of them is usually based on the same overall production steps, such as mixing, shaping and baking. However, large differences in dough composition and production processes are often found between different product categories, including number and type of ingredients, composition of dough, method for formation of dough, additional processing steps, fermentation conditions and baking conditions (W. P. Edwards, 2007). This entails that different mechanisms are in play dependent on dough constituents and variation in production processes.

The starting point for this industrial Ph.D. study has been the Danish pastry production at the Lantmännen Unibake bakery in Hatting, which is located near Horsens, Denmark. This product category was chosen as Danish pastry has large potentials in relation to high-variety manufacturing. However, challenges with process stability of the dough were observed in the Danish pastry production, and this was presumed to be influenced by the raw material properties and the production process conditions. The focus on this project was therefore the dough and characterisation of it.

1.1. OBJECTIVES

The overall purpose of this Ph.D. study is to contribute to a better process understanding in the industrial production of Danish pastry and to assess the effects caused by changes in ingredients and production processes.

The objectives of this project are summarised in the following.

- Elucidating the handling of variables in Danish pastry production and the challenges in relation to adopting mass customisation.
- Identification of key challenges for obtaining robust production processes.
- Selection and establishment of methods for analysis of full formula dough.
- Assessment of the effect of ingredients and production process variables on dough properties.
- Identification of the potentials for implementation of knowledge-based decision-making in the industrial bakery production.

1.2. THESIS CONTENT

This thesis consists of an extended summary and six scientific papers. The extended summary presents some of the main findings from the papers. Four of these are journal papers, and two are conference proceeding papers. They are either published, accepted for publication, submitted to international peer-reviewed journals or in preparation, as indicated. The papers are listed below and cited by their roman numerals throughout the thesis.

I. S. Bech, A.-S. S. Joedal, T. D. Brunoe and K. Nielsen (2018). Mass Customization in Food Industries: Case and Literature Study, in: S. Hankammer, K. Nielsen, F. Piller, G. Schuh and N. Wang (Eds.), Customization 4.0 - Proceedings of the 9th World Mass Customization & Personalization Conference (MCPC 2017). Springer, pp. 519-529.

II. A.-S. S. Jødal and K. L. Larsen. Interpreting the alveogram: Investigation of the relationships between the alveograph parameters, Scientific Reports (submitted).

III. A.-S. S. Jødal and K. L. Larsen. Alveograph characterisation of industrial samples of Danish pastry dough, Cereal Chemistry (submitted).

IV. A.-S. S. Jødal, B. P. M. Jespersen and K. L. Larsen. Comparison of flour and full formula dough properties for different flour qualities, in manuscript.

V. A.-S. S. Jødal, T. P. Czaja, F. W. J. van der Berg, B. P. M. Jespersen and K. L. Larsen. The effect of α-, β- and γ-cyclodextrin on wheat dough and bread properties, in manuscript.

VI. A.-S. S. Jødal, T. D. Brunoe and K. Nielsen. Impact of Dough Property Characterization on Industrial Bread Production, 10th World Mass Customization & Personalization Conference (MCPC 2021) (accepted for publication).

CHAPTER 2. BACKGROUND

Wheat bread is a common food product worldwide, and the process of making a bread is known to many people. Wheat bread is often made from a basis set of ingredients consisting of wheat flour, water, leaving agent such as yeast and sodium chloride, but many other ingredients can also be added (Cauvain, 2015). The breadmaking process can be divided into a number of steps, as a minimum including mixing, shaping, fermentation and baking. Additional processing steps may be applied, and many different methods may be used in the different steps (Cauvain, 2015). After baking, the bread is often stored, and over time staling occurs (Fadda et al., 2014). The time scales for the different steps are very diverse. The mixing time is often within the range of minutes, as a suitable dough normally can be obtained in less than 20 minutes (W. P. Edwards, 2007). The shaping may be composed of several procedures e.g. sheeting, dividing, rounding and moulding, and it is most often also performed in the range of minutes (Spies, 1990). Fermentation time on the other hand ranges from less than an hour to days, dependent on the leaving agent and the temperature (Cauvain, 2009). The baking time ranges from a few minutes to a few hours, dependent on the temperature and type of bread (W. P. Edwards, 2007). After baking, the bread can be stored for several days. In each of these steps, several chemical, biochemical and physical transformations take place (Ooms & Delcour, 2019). The constituents of the flour interact with the other ingredients, as well as the activity of the yeast influences the dough (Ooms & Delcour, 2019). Also the input of mechanical energy to the dough from mixing and shaping affects the dough on an molecular level, as do temperature changes in all steps (Goesaert et al., 2005). Continuous changes in molecular structures at different rates and kinetics take place, and neither dough nor bread is therefore ever in equilibrium. The properties of dough and bread are consequently highly time-dependent (Goesaert et al., 2005).

Danish pastry is composed of more ingredients than bread, and especially the large amount of fat is different from bread. The production of Danish pastry consists of many of the same steps as used for breadmaking, but the lamination process in which the layered structure of dough and fat is formed is only applied in pastry (Ooms et al., 2016). Despites some differences between bread and Danish pastry, wheat flour is one of the main ingredients in both bakery products, and many of the transformations of the wheat flour constituents in the different processing steps are similar.

2.1. WHEAT FLOUR CONSTITUENTS AND THEIR FUNCTIONALITY IN DOUGH AND BREAD

Wheat is the most important cereal in breadmaking worldwide, due to its ability to form a dough when mixed with water with unique viscoelastic properties and gas-holding capacity (Goesaert et al., 2005). Wheat flour consists of multiple constituents, including starch (approximately 70-75 %), water (approximately 14 %), protein (approximately 10-12 %), non-starch polysaccharides, especially arabinoxylans (approximately 2-3 %) and lipids (approximately 2 %) (Goesaert et al., 2005). All flour constituents are known to affect the different steps of breadmaking, but especially starch and proteins are important. Addition of other ingredients and additives can affect the functionality of the flour constituents as well.

The protein fraction of wheat has been divided into gluten and non-gluten proteins, based on functionality and solubility (Wieser, 2007). The nongluten proteins have no or only minor functionality in breadmaking. They constitute between 15 and 20 % of total wheat proteins by weight and are found mainly in the outer layers of the wheat kernel, which is often not used for flour (Goesaert et al., 2005). The gluten proteins are the major storage proteins in wheat and constitute between 80 and 85 % of the wheat proteins (Goesaert et al., 2005). The gluten proteins play a major role in breadmaking, and both the quantity and composition of these are determining for the dough properties and the breadmaking performance (Barak et al., 2013). The gluten proteins are considered to be defining for the flour quality and strength, which are usually assessed based on the rheological properties of a simple flour-water dough (Goesaert et al., 2005). The gluten proteins can be divided into monomeric gliadins and polymeric glutenins, which consist of glutenin subunits linked together by intermolecular disulphide bonds (Wieser, 2007). The glutenins and the gliadins are able to form a gluten network, which is determining for the viscoelastic properties of dough (Wieser, 2007). Glutenins are often assumed to provide strength (resistance to deformation) and elasticity, as they form a continuous network, while gliadins are accountable for viscosity and plasticity, as they are thought to act as plasticisers of the glutenin polymers (Wieser, 2007).

The main constituent in wheat flour is starch. Starch is glucose polymers, which can be separated into two fractions, amylose and amylopectin. Amylose consists of about 500 to 6000 glucose residues bound together mainly by α-(1,4) linkages with very few branches linked through α-(1,6) linkages, and it is therefore essentially a linear polymer (Goesaert et al., 2005). Amylopectin is on the other hand highly branched and much larger, as it consists of about $3 \cdot 10^5$ to $3 \cdot 10^6$ glucose units (Goesaert et al., 2005). The starch in wheat is organised in granules of different size consisting of altering amorphous and semi-crystalline shells (Goesaert et al., 2005). The starch granules may be damaged during milling, which changes the properties of the starch considerably. Damaged starch granules can absorb approximately three times more water than intact starch granules, as well as the damaged starch is susceptible to enzymic hydrolysis, which the intact starch granules are more resistant to (Cauvain, 2015).

In dough mixing, input of mechanical energy transforms flour, water and the other ingredients into a coherent dough through multiple processes. In the beginning of mixing, the flour constituents are hydrated by absorption of water (Gras et al., 2000).

The water is thought to facilitate the unfolding and interaction between the proteins, eventually allowing the gluten proteins to form a continuous cohesive viscoelastic network (Belton, 2005). This process is also facilitated by the input of mechanical energy through deformation (Belton, 2005). It is generally accepted that the gluten network is formed during mixing by continuous depolymerization and polymerization reactions. Both covalent and non-covalent interactions are considered to be important for the formation of the gluten network. Disulphide bonds between cysteine residues on the glutenin subunits have gained a lot of attention, and the formation of disulphide (SS) bonds by oxidation of free thiol (SH) groups on cysteine as well as SH-SS exchange reactions are presumed to be essential in the formation of a three-dimensional network (Dong & Hoseney, 1995; Wieser, 2007). Non-covalent interactions, including hydrogen bonds, hydrophobic interactions and ionic bonds, are also generally accepted to be important for the gluten network structure and thereby the properties of the dough (Ooms & Delcour, 2019; Quayson et al., 2016; Wieser, 2007). Although the non-covalent interactions are much weaker than the covalent bonds, their high number makes their contribution substantial. Different models for explaining the link between the gluten network structure and its properties have been made. Singh & MacRitchie (2001) have proposed to apply the theories from polymer science to dough. The gluten proteins are in this model considered to be polymers of different molecular size, which are entangled at a number of entanglement points (Singh & MacRitchie, 2001). Stretching of coiled chains, slippage at the entanglement points and breakage of chain take place during deformation and thereby determine the viscoelastic properties of the dough (Singh & MacRitchie, 2001). Belton (1999) proposed a loop and train model, in which hydrogen bonds are considered to be very important. In this model, the high molecular weight glutenin polymers (formed by the glutenin subunits) are divided into train regions, which are often associated with β-sheets, and loop regions, which are presumed to be hydrated, mobile strands. When the dough is deformed, the loops will be deformed at first, and then the trains will be pulled apart (Belton, 1999). Other models for the gluten behaviour have also be proposed (Li Vigni et al., 2013).

If the mixing continues beyond the gluten network development, it is generally accepted that the network is partly destroyed, as the proteins disaggregate and depolymerise due to the continuing mechanical stress (Schiedt et al., 2013). The process will also result in release of free water, as the water binding capacity of the proteins is decreased. The starch granules in the flour are agglomerated initially, but they become uniformly distributed in the gluten network during mixing (Peighambardoust et al., 2006). Furthermore, air bubbles are incorporated in the dough during mixing (Kokawa et al., 2012). On a microscopic level, the dough hence consists of a continuous protein network with starch granules and air bubbles embedded (Peighambardoust et al., 2006).

The mixing process is often studied by monitoring the dough resistance during mixing (Cauvain, 2015). During mixing, the resistance increases until it reaches a maximum after which it decreases. The maximum is referred to as optimal dough development, while before the optimum the dough is characterised as undermixed or underdeveloped, and after the optimum as overmixed or overdeveloped (Goesaert et al., 2005). These changes in dough consistency are thought to be mainly related to changes in the gluten protein network (Gras et al., 2000). The amount of energy required to develop the dough to optimal development is dependent on multiple factors, including the mixing speed and the design of the mixer (Chin & Campbell, 2005a), the characteristics of the flour (Chin & Campbell, 2005b), the water content of the dough (Belton, 2005) and the type and the quantity of other ingredients (Calderón-Domínguez et al., 2005).

During fermentation, the leaving agent, which is most often yeast, but may also contain other microorganisms such as lactic acid bacteria, increases the dough volume by gas production (Cauvain, 2015). Enzymes from e.g. flour and yeast degrade some of the accessible starch to sugars, and these are consumed by the yeast, which in return releases CO_2, ethanol and other metabolites (Struyf et al., 2017). The gluten network ensures retention of the gas produced by the yeast, as well as other changes in the gluten network may also take place (Goesaert et al., 2005). The size of the gas cells grows during fermentation, while the number of gas cells are not increased. This is because CO_2 produced by the yeast is not able to form new gas cells, as the pressure required for a single molecule of CO_2 to create a new gas bubble is infinitive for a system, where the interfacial tension is constant (Ooms et al., 2016). The gas cells in the dough originate instead from incorporation of air during mixing and processing. As the gas cells continues to increase, the cell walls between neighbour gas cells may rupture, and the gas cells coalesce to form a single, larger gas cell (van Vliet et al., 1992).

During baking, a range of different processes occur, which transforms the foam structure in the dough to a sponge structure in bakery products. The foam structure is essential for the volume increment during baking, called oven spring. The dough expands due to thermal gas expansion, release of solubilised CO_2 and yeast activity, and this takes place as long as the gas cells in the foam structure are intact (Cauvain, 2015). At some point during baking, some of the membranes between the gas cells rupture, as the starch gelatinises, and as the proteins are subjected to several changes including thermal denaturation, resulting in a sponge structure with a continuous gas phase (Cauvain, 2015). Starch gelatinisation is an important process during baking. Starch granules absorb some water at room temperature causing swelling of the granules, but this swelling is reversible (Goesaert et al., 2005). If the starch granules are heated to temperatures above the gelatinisation temperature in the presence of sufficient water, the starch granules gelatinise (Goesaert et al., 2005). Starch gelatinisation is a series of changes taking place over a broad temperature range leading to irreversible destruction of molecular order. These changes include melting of amylopectin crystals, dissociation of the amylopectin double helices, amylose leaching from the starch granules, as well as swelling and distortion of the starch granules (Goesaert et al., 2005). The leached starch forms a continuous network by entanglement of the polymers (Goesaert, Slade, et al., 2009). The gelatinisation temperature is affected by the water content and the presence of other ingredients (A. Salvador et al., 2006; Schirmer et al., 2014). In general, dough does not contain enough water to fully gelatinise the starch, and the structure of the starch granules is therefore partially retained (Cauvain, 2015). The gluten network is also subject to changes during baking, making the network more rigid (Scanlon & Zghal, 2001). The proteins denature upon heating causing various changes in protein network. These changes are considered to include interchanges in disulphide bonds and sulfhydryl groups, formation of new disulphide bonds and changes in the hydrophobicity of the protein surfaces causing aggregation (Goesaert, Slade, et al., 2009; Weegels et al., 1994). This result in a permanent and thermoset gluten network.

During storage, bread and similar products stale. Staling is defined as loss of freshness and consumer acceptance (with exception of microbial spoilage) (Gray & Bemiller, 2003). Staling is primarily an organoleptic assessment of bread freshness and is therefore multifaceted, but change in crumb firmness is often used as a measure for it (Gray & Bemiller, 2003). Staling is a complex phenomenon, and the molecular mechanisms are not fully understood. It is generally agreed that it is related to changes in several bread constituents (Goesaert et al., 2005). The most important factors seem to be starch transformations, starch-gluten interactions and water migration (Fadda et al., 2014). The main starch transformation during storage is amylopectin retrogradation. Amylopectin retrogradation is a process, in which the gelatinised starch molecules, especially the outer branches of amylopectin, re-associate to double helical structures, after which crystalline regions are formed (Cauvain, 2015). Water is incorporated in the crystalline starch, and the water distribution is therefore also affected (Gray & Bemiller, 2003). The water bound in the crystalline starch can no longer plasticise the different amorphous networks, including the thermoset gluten and the amorphous amylopectin, and this lack of plasticity further increases crumb firmness (Goesaert, Slade, et al., 2009). Amylopectin retrogradation is strongly presumed to be part of the staling mechanism, as well as other processes have been shown to be involved (Gray & Bemiller, 2003). Contrary to amylopectin, amylose is not presumed to be involved in staling during storage (Gray & Bemiller, 2003). Amylose retrogrades rapidly upon cooling after baking and forms a continuous network, which has been shown to be essential for the crumb structure (Goesaert et al., 2005). Amylose chains form double helices and crystallise, as well as amylose may form single helical complexes with lipids (Conde-Petit & Escher, 1995). Starch-gluten interactions are also important for staling, as more hydrogen bonds between gluten and starch are formed during storage, possibly due to redistribution of the water, which increases the crumb firmness and thereby staling (Every et al., 1998; Goesaert, Slade, et al., 2009). Beside the redistribution of water among the flour constituents described above, other redistributions of water also occur. In freshly baked bread, the moisture content is higher in the bread crumb than in the crust. During storage, water migrates from crumb to crust to reduce this difference, causing a more rigid crumb and a reduced crust crispness (Gray & Bemiller, 2003). Water may also evaporate from the bakery product, further accelerating staling (Gray & Bemiller, 2003).

2.2. PROCESSES IN DANISH PASTRY PRODUCTION

Danish pastry is made from fermented laminated dough, which consists of altering layers of predough and bakery fat (Cauvain, 2015; Ooms et al., 2016). The dough can be used for multiple types of Danish pastry with different shapes and fillings (Cauvain, 2015). Danish pastry is characterised by a flaky texture when baked.

Danish pastry predough consists of wheat flour, water, yeast, sugar and salt, but can also contain bakery fat (typically margarine, butter or shortening), eggs and milk powder, as well as different improvers and other additives (Cauvain, 2015; Ooms et al., 2016). The fat may therefore both be present as in-dough fat and as roll-in fat from the lamination.

The flour used for pastry is determining for the final product, as it is generally accepted that strong flour results in a higher pastry lift than weak flour (Wickramarachchi et al., 2015). Flour tolerant to overmixing is assumed to be advantageous for pastry production, as the dough is processed in multiple steps (Ooms et al., 2016). The rheological properties of the gluten proteins are in general accepted to be more important than the flour protein content (Cauvain, 2015; Wickramarachchi et al., 2015). Hay (1993) found that for puff pastry, the pastry height and volume were positively correlated with mixing and extensional properties of the flour as well as flour protein content. He stated that the flour should have a high extensibility to avoid rupturing of the predough layers (Hay, 1993). Sliwinski et al. (2004b) stated that flour for puff pastry should have a high strain hardening coefficient and a low strain rate-dependency of stress, as this promotes the formation of thin dough films. Sliwinski et al. (2004b) did not find that puff pastry volume was significantly correlated with neither flour protein content nor failure strain, which is a measure of extensibility, but they stated that the flour should contain a high content of glutenin. The importance of glutenin is in agreement with the results from Hay (1993). Addition of flour improving agents, which are considered to strengthen the gluten network by increasing the formation of disulphide bonds, has also been shown to increase the pastry lift for yeasted pastry (Ooms et al., 2018).

The in-dough fat is often added to the predough in the form of pastry trimmings or scrap dough, which are e.g. dough edges cut off after lamination before the shaping of the individual products (Cauvain, 2015). The roll-in fat in the pastry trimmings from one production run can therefore serve as the in-dough fat in the next, while for the first production runs, at which no pastry trimmings are available, the fat must be added directly to the ingredients before mixing of the predough (Ooms et al., 2016). The pastry trimmings are often added directly to the mixer together with the other ingredients. It is important to be aware of age, temperature and amount used of the pastry trimmings to avoid unwanted product variability (Levine, 2007).

The predough is made by mixing the ingredients, typically using straight dough method, in which all the ingredients are mixed in a single step (Cauvain, 2015). The mixing speed, the mixing time and the degree of the dough development at the end of mixing are all dependent on the product and the nature of the production line at the bakery. In general, but pastry doughs are underdeveloped at the end of mixing, as further dough development occurs during lamination (Ooms et al., 2016; Renzetti et al., 2015). Often, the dough is therefore only mixed until it is homogenous (Ooms et al., 2016). It is generally agreed that the dough should be optimally developed after the final laminating step in order to avoid breakdown of the gluten network, and the mechanical energy input from mixing and sheeting should therefore not exceed the optimal level (Ooms & Delcour, 2019). However, there seems to be a lack of data on to what degree the predough should be undermixed after mixing to obtain an optimally developed gluten network after laminating (Ooms et al., 2016). This is further complicated by the lamination with fat, as the fat layers also affect the dough properties and development (Renzetti et al., 2015). The predough is typically relatively cold, as the roll-in fat requires a relative low processing temperature, and predough and roll-in fat must therefore have similar temperature (Cauvain, 2015). This can be obtained by e.g. cooling of ingredients, using ice-water and/or by a gas cooling system, which injects e.g. CO_2 during predough mixing (Ooms et al., 2016).

Prior to lamination, fat is folded into the predough. Different methods can be used for this, dependent on whether it is done manually or industrially. The purpose is to obtain one fat layer between two predough layers (typically), which is often obtained industrially by extrusion of respectively predough and fat (Cauvain, 2015). The ratio between predough and fat in Danish pastry dough is dependent on the product type and can vary from 12.5 to 60 % (w/w) fat relative to predough, dependent on how lean or rich the product should be (Baardseth et al., 1995; Cauvain, 2015). The amount of fat is often associated with texture, e.g. firmness, sponginess and crispness, as well as colour of the final Danish pastry product (Baardseth et al., 1995). The predough and the fat should have comparable plasticity to obtain proper development of the layers (Bousquières, Deligny, Challois, et al., 2014; Ooms et al., 2016). If the fat is too firm and brittle or the predough is too soft, the fat may break through the predough layers and form irregular or discontinuous fat layer, resulting in uneven or poor pastry lift (McGill, 1975). Vice versa, if the fat is too soft or the predough is too stiff, the fat may not withstand the mechanical stress during sheeting and can therefore break down and migrate out in the predough. This result in coalescence of the layers and poor volume increase during baking (McGill, 1975). The plasticity of fat is mainly dependent on its crystal form and the solid fat content (Pareyt et al., 2011).

A dough with altering and discrete layers of predough and fat is produced by lamination. In the process of lamination, the dough is in turn folded (to obtain a specific number of fat layers) and sheeted (to reduce the dough thickness). The process of folding and sheeting is repeated a suitable number of times. Danish pastry dough and similar yeasted pastry doughs are typically folded to obtain 16-50 (theoretical) fat layers, while puff pastry, which does not contain yeast, typically has 130-250 (theoretical) fat layers (Cauvain, 2015; Ooms et al., 2016). The number of fat layers are determining for the product volume and height, as well as the crumb structure. In general, increasing number of fat layers result in increasing pastry height, until a point after which the pastry height starts to decrease (Bousquières, Deligny, Challois, et al., 2014; Deligny & Lucas, 2015; McGill, 1975). Few fat layers might occasionally result in large product height, but it is often related to an irregular crumb structure (Cauvain, 2015; Deligny & Lucas, 2015). On the other hand, too many fat layers are associated with fragmentation of the fat layers (Bousquières, Deligny, Challois, et al., 2014), which in the final product result in a bread-like crumb and a loss of flakiness (Cauvain, 2015; Deligny & Lucas, 2015). The structure with altering layers of predough and fat entails that the gluten network is not continuous in three dimensions across the entire dough as would be the case for bread. Instead the laminated dough is considered to contain thin layers of separate gluten network within each predough layer between the fat layers (Baardseth et al., 1995). It has been shown that the fat layer thickness varies within laminated Danish pastry dough, but strengthening of the gluten network results in more constant fat layer thickness (Bousquières, Deligny, Riaublanc, et al., 2014; Ooms et al., 2017). Furthermore, the fat layers do not remain intact during lamination, as interconnections between the predough layers are created (Bousquières, Deligny, Riaublanc, et al., 2014; Ooms et al., 2017).

After each lamination step, elastic recoil of the dough sheets might be observed (Bousquières, Deligny, Riaublanc, et al., 2014; Ooms et al., 2017). Elastic recoil is the recovery of dough thickness after sheeting, which causes the dough to be thicker than the gap between the rollers (Deligny & Lucas, 2015). Elastic recoil is especially observed in the direction of the last sheeting, as the gluten network is aligned with the sheeting direction, resulting in inbuilt stress that leads to shrinkage during relaxation (Ooms et al., 2017). Elastic recoil in Danish pastry dough has also been shown to affect the continuity of the fat layers and result in curling of them, again especially in the last sheeting direction (Bousquières, Deligny, Riaublanc, et al., 2014). Relaxing time between the folding steps can be used to reduce the shrinkage caused by elastic recoil, as the gluten network is in a stressed state after each lamination step which relaxes with time (Sliwinski et al., 2004b). The dough properties are dependent on whether the dough is stressed or relaxed, as e.g. the dough strength in deformation decreases during relaxation (Ooms et al., 2017).

After lamination, the dough is usually sheeted, cut and shaped into individual products, as well as different fillings, such as custard or jam, and toppings, such as nuts or nib sugar, can be added. The individual products are subsequently fermented, at which gas production by the yeast increases the volume of the dough (Deligny & Lucas, 2015). Fermentation is normally conducted at temperatures lower than those usually used for bread in order to avoid melting of the roll-in fat and to preserve the fat layers (Cauvain, 2015). During fermentation, yeast produces CO_2 and other metabolites, of which the CO_2 is primarily accountable for the volume expansion (Meerts, Vaes, et al., 2018). The produced CO_2 is assumed to be first distributed to the aqueous phase of the dough, and when this phase is saturated, further CO_2 diffuses to the pre-existing gas cells and enlarge them (Ooms et al., 2016). The gas cells in predough originate from air entrapped during predough mixing as well as during the folding operations. Gas cells can also be observed in the fat layers, which may originate from the original block of fat, the extrusion step or the predough-fat interface (T. Lucas et al., 2018). Deligny et al. (2017) found that most of the volume increase in Danish pastry during fermentation could be assigned to air bubbles in the predough layers, in which the bubbles are small and quite round. Less than 10 % of the overall inflation during fermentation was caused by the air bubbles in the fat layers, in which the bubbles were quite large and eye-shaped (Deligny et al., 2017). Yeast is presumed to cause rupture of the fat layers by production of CO_2 during fermentation, which is why yeasted pastry is made with fewer fat layers than puff pastry (Cauvain, 2015; Deligny & Lucas, 2015).

After fermentation, the Danish pastry products can be frozen, if they are intended to be sold as bake-off. The advantage of prefermented bake-off is that they can be taken from the freezer and put directly in the oven for baking (Cauvain, 2015).

The Danish pastry products can be baked after fermentation or freezing. For pastry, it is generally accepted that during baking water vapour is trapped in the layered structure and creates the volume increase, which is often referred to as pastry lift. It is presumed that the fat layers act as barriers against diffusion of water vapour from the predough, forcing the predough layers to expand due to the pressure underneath (McGill, 1975). It is generally accepted that the barrier property is dependent on the continuity of the fat layers after the last sheeting step (McGill, 1975). However, recent studies have challenged this statement and found that at least for yeasted pastry, more factors are decisive for the pastry lift (Bousquières, Deligny, Challois, et al., 2014; Deligny et al., 2017; Ooms et al., 2018). In Danish pastry, yeast activity during the early baking phase, release of CO_2 solubilised in the aqueous phase and thermal gas expansion in the gas bubbles have been shown to contribute to the volume increase during baking (the same mechanisms as in bread baking) (Ooms et al., 2018). Accordingly, the contribution from the entrapment of water vapour to the pastry lift, which is presumed to be the main mechanism in puff pastry, is thus smaller for Danish pastry (Ooms et al., 2018). Bousquières, Deligny, Challois, et al. (2014) found that the number of discontinuities in the fat layers resulting in interconnections between the predough layers increase with increasing number of layers, while the length of the discontinuities was independent on the number of fat layers. However, at the same time, the pastry lift increased, which contradicts the assumption that discontinuities in the fat layers are the reason for the decreasing pastry lift. Deligny et al. (2017) and T. Lucas et al. (2018) suggest that the size of the fat fragments is more important for the pastry lift than discontinuities in the fat layers. Ooms et al. (2018) further found that it is important with some interconnections between the predough layers, as the predough layers may otherwise slide apart during baking. Eye-shaped bubbles, which are characteristic for pastry products, primarily arise from expansion of the gas cells in fat fragments of a sufficient size during fermentation and especially baking (Deligny et al., 2017; T. Lucas et al., 2018). Dough with few fat layers contain more large fat fragments with air bubbles, and during baking these bubbles often collapse and release the air to the surroundings (T. Lucas et al., 2018). Doughs with many fat layers contain primarily small fat fragments originating from extensive fragmentation of the fat layers. A small fat fragment only rarely contain an air bubble, and if it does, the resulting bubble in the final product tends to be more round, like the bubbles observed in the predough parts, and not eye-shaped (T. Lucas et al., 2018).

The volume increase due to oven rise is much larger for pastry compared to bread, and the dough layers of pastry are therefore also stretched more extensively compared to bread dough (Deligny & Lucas, 2015; McGill, 1975). It is assumed that the heat-induced changes of the gluten occur in a similar way in bread and pastry. However, the fat in pastry melts during baking, and the melted fat may be absorbed by the dough, which may interfere with the polymerisation of gluten (Ooms et al., 2016). Another important mechanism during baking is gelatinisation of starch. Danish pastry contains less water and contain additional ingredients compared to bread, which are expected to limit the gelatinisation of starch and thereby increase the gelatinisation temperature and possibly result in a higher retention of granule integrity (Ooms et al., 2016; Schirmer et al., 2014).

An example of the steps in an industrial Danish pastry production can be seen in the flowchart in Figure 2-1. The products from this production system are sold as bake-off, which means that the product is prefermented, frozen dough. The baking of the products is performed by the customers.

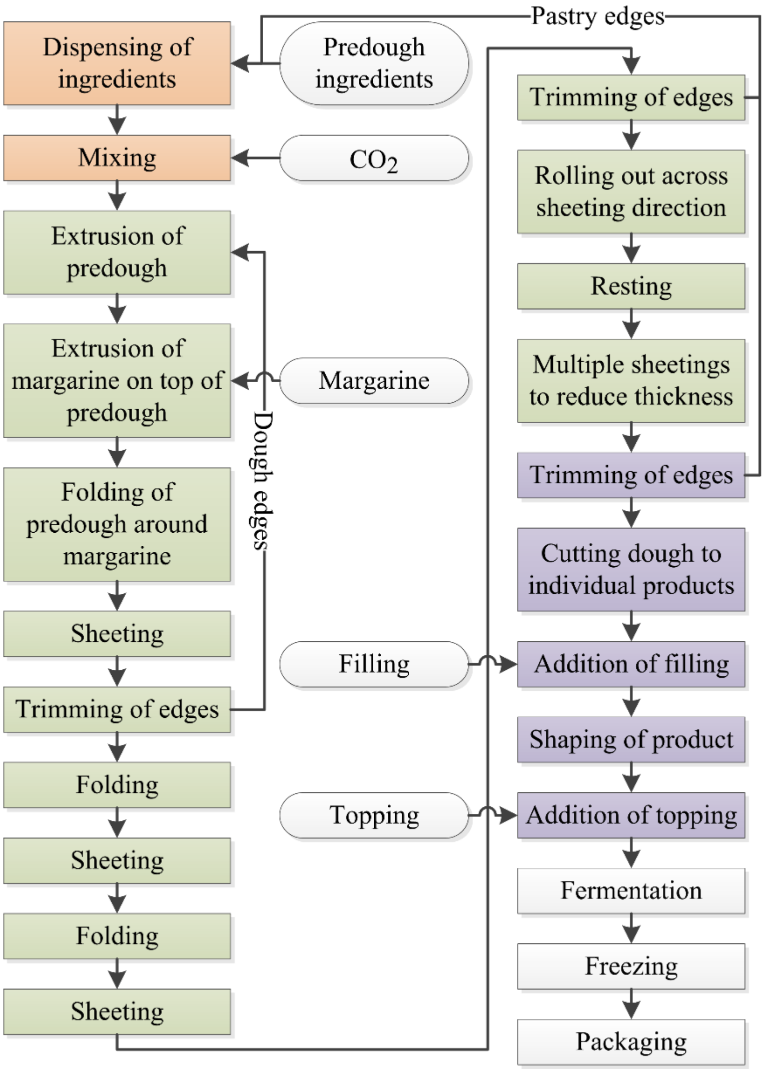

Figure 2-1: An example of the steps in the industrial production of Danish pastry bake-off products. The mixing, lamination and make-up parts are indicated by orange, green and purple background colour, respectively. The predough ingredients include flour, water, egg, sugar, yeast and improvers. In the first trimming of dough edges, the cut-off does not contain margarine, and it is therefore returned to the extruder. In the subsequent two trimmings of edges, the predough has been laminated with margarine, and the cut-off is therefore used in the mixing of the predough to provide in-dough fat. Different configurations can be found in the make-up part dependent on the type and shape of product.

In general, the production can be divided in different parts, consisting of mixing, lamination, make-up, fermentation, freezing and packaging. Several parts of the productions can be further divided into processes and unit operations, as seen in Figure

2-1. In the mixing part, the ingredients for the predough are dispensed in a mixing bowl. Pastry trimmings are used to supply the in-dough fat. In the beginning of the production, at which no pastry trimmings are available, margarine is added to the other predough ingredients. The predough is mixed, and CO_2 is injected to the mixing bowl during mixing to lower the predough temperature. In the lamination part, the predough is first extruded, and margarine is extruded on top of just under half of the predough sheet, after which the other half of the predough sheet is folded on top of the margarine layer to obtain one layer of fat between two layers of predough. The dough is in turns folded and sheeted. In each folding step, four or six fat layers are made to obtain a total of typically 24 (theoretical) fat layers. The total number of fat layers are dependent on the type of product. After the final folding, the dough is rested, before it is sheeted multiple times to reduce the thickness of the dough sheet. In the make-up part, the dough is in general cut and shaped into individual products as well as fillings and toppings can be applied. Different configurations are used dependent on type and shape of the product. A range of different shapes can be made, including plait, swirl, crown, coronet, fan, birkes and bun as well as bar and tart, and some of them can be made in different sizes. The filling can be jam, custard or something else, allowing a range of different flavours as e.g. different fruits can be used for the jam. Two fillings can also be added in the same product. Different types of topping can also be used. After the make-up part, the products are fermented, frozen and packed. The predough mixing and the preparation of some of the fillings are made as batch production, while the remaining part of the production is continuous.

The final product is dependent on several variables, including dough recipe, margarine content, number of fat layers, shaping of the product, and application of filling and topping. The quality of the final product is highly dependent on the first part of the process, in which the laminated structure of the dough is made, while much of the variety is obtained in the last part of the process.

All steps are primarily performed by machines, and only minor procedures are conducted by hand, such as moving the mixing bowl and refilling of dusting flour, margarine, fillings and toppings. However, the operators at the production line are important for the manufacturing process.

2.3. HANDLING OF VARIABLES AT INDUSTRIAL BAKERIES

The production of bakery products at an industrial level today is to some extent characterised by a craft approach. The development of new products is usually based on a trial and error approach, relying on the know-how and craftmanship of experienced bakers (Kristiawan et al., 2017). The bakery products are manufactured in an industrial setting where most processes are automated, however, the machine settings are determined by trial and error, and adjustments are made manually (Bech, Brunoe, Nielsen, et al., 2019; Li Vigni et al., 2009). Compared to the craft baker, the baker in an industrial bakery is in less contact with the dough, making it more difficult to regularly assess the dough at the different processing stages (Cauvain, 2015). However, the control of the dough during production is still relying on the baker in the industrial bakeries, as at least in some companies only a limited number of machine settings are regulated automatically based on measurements (Bech, Brunoe, & Nielsen, 2019). At the same time, the dough is exposed to more stress and mechanical impacts in the industrial bakeries compared to in the craft bakeries, and this entails higher requirements to the functionality of the dough in the industrial production (Cauvain, 2015; Kvistgaard et al., 1993). There are many reasons why the adjustments of this process have not been automated to a higher extent. This includes a high number of adjustable variables, the variability in the properties of the ingredients, especially wheat flour, and a lack of suitable analysis methods for on-line or at-line monitoring (Li Vigni et al., 2009, 2013; Ulrici et al., 2008).

The mills and the ingredient suppliers are often looked to for knowledge and problem solving, as much of the knowledge about the ingredients and their effects on the process are found there today (Cauvain, 2015). The mills conduct a range of different analyses on the flour to assess the quality, but the bakeries are not able to fully apply these results in the production (Li Vigni et al., 2013). An increasing number of additives are used in dough to improve different properties of the dough and the final product, but the complex nature of additives result in much of the knowledge about the additive functionality is located at the ingredient suppliers and not at the bakeries (Cauvain, 2015; Kvistgaard et al., 1993). The ingredient supplier may only have studied the ingredient in a limited number of applications and is therefore not able to foresee the effects in all relevant cases, as well as interaction effects may be difficult to predict (Sharp, 2001). The bakeries have made various requirements to the ingredient properties based on experience and possibly unsystematic testing (Li Vigni et al., 2010, 2013). These requirements are typically established to decrease the variability of the dough between different batches, increase the process stability and keep the product quality as constant as possible (Li Vigni et al., 2010, 2013).

All these factors entail various challenges at industrial bakery productions. The craft-approach in the development of new products causes a long time to market, defined as the duration needed from initial idea to delivery of the first product to a customer. The knowledge of the effects and the interaction between the ingredient variability, the conditions of the surrounding environment, the production processes and the final product is insufficient and often based on experience (Kristiawan et al., 2017). No systematic, preventive adjustments based on changes in e.g. ingredient properties or environment conditions are made before the start of the production. Instead the production processes are continually adjusted by the operators according to manual assessment of the dough (Bech, Brunoe, & Nielsen, 2019; Bech, Brunoe, Nielsen, et al., 2019). The combination of insufficient and experience-based knowledge on the effects of the adjustable variables entails that many unsystematic adjustments are made, especially in the beginning of the production. This result in long ramp-up time, as the efficiency is lowered, and large amounts of waste of materials, as products of insufficient quality are discarded.

2.4. FLOUR CHARACTERISATION METHODS

While quantitative measurements of dough properties are rarely performed in the bakeries, multiple analysis methods for flour characterisation are available and industrially applied (e.g. at the mills). It is generally accepted that flour is one of the most important ingredients for bread quality, as the flour is highly determining for the properties of the dough and final product, and quantitative analyses are therefore widely applied for benchmarking of flour. The flour analysis methods can be divided into chemical and physical methods. The chemical methods are related to fundamental chemical properties of the flour, such as protein, ash or water content (Cauvain, 2015). The physical methods are rarely related to fundamental measurements, but are often descriptive empirical measurements of the behaviour of dough (Cauvain, 2015).

There is a long history of empirical measurements within the cereal industry, as the empirical methods often attempt to imitate breadmaking processes, such as mixing or bubble growth (Dobraszczyk & Morgenstern, 2003). These methods are performed on a dough, but as the methods are used as standards in assessment of flour properties, the doughs often consist of only flour, water and possibly sodium chloride. The physical analysis methods attempt to assess different properties of the flour, including the water absorption capacity of the flour (amount of water added to the flour to obtain a dough which reaches a specific resistance during mixing), gelatinisation of starch during heating of flour-water-suspension, as well as deformation properties of dough with either variable or fixed water content (Huen et al., 2018b). Thus, these methods often attempt to assess the rheological properties of dough. The empirical measurements have multiple advantages, as they are often easy to perform, they provide information for different processes, and many of these methods are industrially used as standards (Dobraszczyk & Morgenstern, 2003). Some of the most used empirical standard methods are farinograph and mixograph, which both assess the mixing properties of dough, as well as extensograph and alveograph, which assess the uniaxial and biaxial extensional dough properties, respectively. It is impossible to compare the results from the different empirical tests, as the sample geometry differs and is not well-defined, and the rate and the extent of deformation as well as the stress are variable, uncontrolled and complex (Stojceska & Butler, 2012). Additionally, the standard dough composition often differs among the methods (Cauvain, 2015). For instance, in the farinograph method the analysed dough consists of flour and a variable amount of water as standard, while in the standard alveograph method a dough consisting of flour, sodium chloride and a fixed amount of water is applied (Cauvain, 2015). The complete range of data obtained from the various tests are often reduced to a single or few parameters, leading to an inherent loss of information. The deformation conditions might also be inappropriate to mimic the practical processing situations. The rate of extension during fermentation and oven rise has been calculated to be between $5 \cdot 10^{-4}$ and $5 \cdot 10^{-3}$ s^{-1}, while the maximum rate of extension for extensograph and alveograph analyses are two or more orders of magnitude greater (Bloksma, 1990). Furthermore, results from different methods for assessing the mixing properties of flour can be inherently difficult to compare, as the properties of the dough are dependent on different geometries of the analysis instrument (Ktenioudaki et al., 2010; Wesley et al., 1998), as well as the mixing speed and work input (Chin & Campbell, 2005a, 2005b).

Dough can also be characterised using fundamental rheological methods (Dobraszczyk & Morgenstern, 2003; Song & Zheng, 2007). The fundamental rheological tests used for dough are typically either dynamic oscillation (I. Lucas et al., 2019; Meerts, Vaes, et al., 2018; van Bockstaele et al., 2008), creep and stress relaxation (de la Horra et al., 2015; Hernández-Estrada et al., 2014; F. C. Wang & Sun, 2002) or large deformation extension (Kokelaar et al., 1996; McCann et al., 2016; Sliwinski et al., 2004a). With these methods, the deformation or strain is controlled and quantifiable, and the resultant force or stress is measured. They thus measure a well-defined property independently of the sample geometry, and the results are consequently easier to compare. However, these methods also have their disadvantages, as it is often more difficult to perform the fundamental tests, and the results are harder to interpret and relate to the breadmaking process (Dobraszczyk, 2004b). These measurements are therefore often not applied industrially (Dobraszczyk, 2004b).

A wide range of different analysis methods are available, but many of them are aimed at flour characterisation and are therefore not used for characterisation of the full formula dough at the bakeries. Although flour is one of the most important ingredients for the properties of the final product, the relations between the results from the flour analysis methods and the bread quality are still not fully understood (Li Vigni et al., 2009; Spies, 1990). Many of the analysis methods mimic breadmaking steps, but they may not be suitable for prediction of the behaviour in the industrial production (Ktenioudaki et al., 2011; Li Vigni et al., 2009; Stojceska & Butler, 2012).

2.5. MASS CUSTOMISATION AND THE BAKERY INDUSTRY

There is an increasing demand for product variety and more individualised products today (Koren, 2010; Y. Wang et al., 2017). In manufacturing, this is entailed by smaller batch sizes, shorter product life cycles and shorter time to market, which often pose several challenges for traditional dedicated manufacturing systems (H. A. ElMaraghy & Wiendahl, 2009). The demand for higher product variety can to some extent be addressed by the business strategy mass customisation, which aims at offering customers individualized products at near mass production costs (Pine, 1993). The concept does therefore call for manufacturing systems that can satisfy personalised requirements, while at the same time having efficiencies comparable to mass production. Several approaches can be used in the manufacturing systems, as it needs to be flexible and agile for high-variety production (Boland, 2006; F. Salvador et al., 2009). F. Salvador et al. (2009) states that mass customisation is not a state that can be reached, but rather the transition towards this goal, and every company must find their own way. Nevertheless, to achieve mass customisation three fundamental capabilities are essential, which are solution space development, robust process design and choice navigation (F. Salvador et al., 2009). Solution space development is the identification of those product attributes the customers want the most to diverge, after which the business can define which variants they offer and which they do not (F. Salvador et al., 2009). Robust process design involves reusing or recombining existing organizational and value-chain resources, and this capability is therefore vital in order to deliver customized solutions with efficiency close to mass production (F. Salvador et al., 2009). Choice navigation is supporting the customers to identify their solution and at the same time minimise the complexity and the burden of choice (F. Salvador et al., 2009).

Mass customisation is largely adopted for discrete, durable goods, but it can also be applied in the food industry (Boland, 2006; F. Salvador et al., 2009). Within food, both sensory performance, such as shape, colour and taste, and functional performance, such as nutritional requirements, can be customised (Boland, 2006). Customisation is most widespread in the fast food industry of products like burgers, pizzas and sandwiches, as the individual components can be combined according to the customer’s preference in the shop (Boland, 2006). Furthermore, multiple configurators for customisation of other food products can be found on the internet as shown by Kolb et al. (2014). However, many of the companies customise only the packaging, and some companies represent craft production rather than mass customisation (Kolb et al., 2014). Food manufacturing processes are characterised by challenges that are not in the same way experienced in the production of durable goods, as covered by McIntosh et al. (2010). This includes e.g. chemical changes and decay of ingredients and products, production methods and design of product as well as cleaning and distribution requirements (McIntosh et al., 2010). Nevertheless, there is a large potential for adopting mass customisation in the food industry (Bech, Brunoe, Nielsen, et al., 2019; McIntosh et al., 2010). This would also be a major competitive parameter, especially if competing companies do not possess these competences (McIntosh et al., 2010).

In paper I, the challenges in adopting mass customisation for each of the three fundamental capabilities were uncovered for the Danish pastry production in Hatting. A short recap of the findings in paper I is given here. We found that for solution space development, the product development was unsystematic and based on know-how and craftsmanship, and the customer preferences were not collected systematically or directly. No guideline nor formal strategy for the development of new products was therefore available, which is important for defining a solution space for the product category. For the robust process design, the company had insufficient knowledge of the ingredient and process properties and their effect on the final product. The production processes were controlled empirically by trained employees, and there was no or very limited digitalized interconnection between the different machines. No quantitative measurements of the dough functionality were made during production. The missing or tacit knowledge of ingredients and production processes as well as the many manual configurations made it difficult to achieve a more robust and flexible production, which is necessary for adopting mass customisation. The choice navigation was based on conversation with the customer, who could pick products from a catalogue, but also propose new variants. The time to market for new products was unknown. As the choice navigation was primarily based on know-how, improvements could therefore also be made for this capability. Several challenges were identified for the company, which should be assessed before mass customisation can be effectively adopted. Many of the challenges were related to the capability of robust process design, and the challenges in the production process must be handled before adopting mass customisation.

2.6. CHALLENGES IN DEVELOPMENT OF ROBUST PROCESSES IN INDUSTRIAL BAKERIES

Much research has been conducted within the cereal science over the years, and the sum of knowledge is constantly increasing. Cereal science is complex with many variables and processes, and many of these are therefore still not fully understood (Cauvain, 2015). Much of the research has been made on breadmaking, but progress has also been made in the understanding of Danish pasty in the recent years (Bousquières, Deligny, Riaublanc, et al., 2014; Deligny et al., 2017; Ooms et al., 2018).

Despite this, the industrial production of Danish pastry products is to some extent still characterised by a craft approach (Bech, Brunoe, & Nielsen, 2019; Bech, Brunoe, Nielsen, et al., 2019; Kristiawan et al., 2017). In the previous sections, some of the reasons for this are covered. These include among others a lack of knowledge on raw materials and processes, an unsystematic approach to testing and adjustments, a high number of variables and a lack of industrially suitable dough analysis methods. A few studies with pastry in an industrial context have been made, but these focus mostly on varying various parameters and measuring the effect on the final product (Besseris, 2015; Shibata et al., 2008). Other studies of pastry are often made in a laboratory setting (Bousquières, Deligny, Challois, et al., 2014; T. Lucas et al., 2018; Ooms et al., 2018). The results from these studies can be hard to transfer to an industrial context, as other variables such as temperature fluctuations and flour quality variability may have a large impact in the industrial production (Li Vigni et al., 2013). Furthermore, the analysis methods applied in the studies are often labour-intensive and require specialised knowledge and technical skills. They can therefore be hard to perform industrially, especially as there is only a very limited tradition within the bakery industry to perform analytical measurements (Cauvain, 2015; Kvistgaard et al., 1993). Quantitative measurements of the dough properties are however essential to obtain a better control of the industrial production and thereby obtain a more robust and flexible manufacturing system. This would also be one of the first steps towards high-variety production and adopting mass customisation.

CHAPTER 3. ALVEOGRAPH ANALYSIS AND ITS PARAMETERS

In this project, the alveograph method is applied to assess the properties of dough. This is performed on an apparatus called an alveograph, which is manufactured by Chopin Technologies (Villeneuve-la-Garenne, France). The alveograph method is an empirical method which assesses the deformation properties of the dough by biaxial extension and more specifically bubble inflation (Dobraszczyk, 2004b). This method was chosen as biaxial extension was considered to be relevant for Danish pastry dough, which experiences large biaxial deformation during lamination, fermentation and baking. Furthermore, it is possible to assess the mixing properties of dough on the alveograph apparatus by the consistograph method.

The development of the alveograph started in the 1920s by Marcel Chopin (Chopin, 1927), and through multiple improvements of all parts of the method over the years, it has been developed into its present form. In the alveograph method, the rheological properties of dough consisting of flour, water and sodium chloride as standard are assessed by measuring the pressure during inflation of a dough bubble (Dubois et al., 2008). This bubble inflation is considered to mimic the air bubble growth in the dough during fermentation and in the initial stages of baking (Dubois et al., 2008). The alveograph method is commonly used in some parts of the world for assessment of flour quality and benchmarking, which is why the most common alveograph parameters are widely applied, and it is generally accepted how these parameters are interpreted (Dobraszczyk, 2004b).

As the use of the alveograph method is widespread, the complete process from the flour to bubble inflation analysis has been standardised (e.g. AACC method 54-30.02) and is performed on the alveograph and the associated equipment (AACC, 2009a). An overview of the steps in the alveograph analysis can be seen in Figure 3-1. In the standard method, the flour is added to the mixing chamber (in the alveograph) and sodium chloride solution is automatically added. A fixed amount of water (corrected according to the water content in the flour) is used for the preparation of the dough. A protocol for adjusting the water addition according to the water absorption of the flour is also available (AACC, 2009b). The temperatures of mixing chamber, resting chamber, test chamber and of the water are controlled. The dough is mixed for 8 minutes, after which five dough pieces are extruded, rolled and cut out to five similar-shaped dough discs, which are rested. 20 minutes after the mixing stopped, the dough discs are clamped into the sample holder and inflated with air into dough bubbles using an air flow rate of 96 L/hour, one by one in the same order as they were prepared. The dough bubbles are inflated until rupture, and the inflation pressure is measured as a function of time. An average curve is made based on the five pressure curves, and multiple alveograph parameters are determined from this curve.

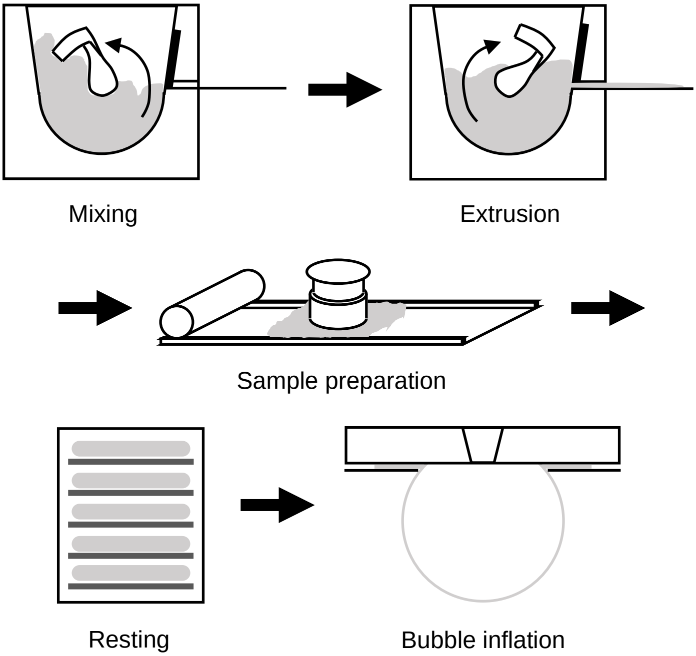

Figure 3-1: The steps in the alveograph method. In the first step, water and flour are mixed to form a dough, which is subsequently extruded, and dough pieces are cut off. The dough pieces are rolled out, and circular dough pieces are cut out using a cutter. The dough pieces are rested, after which they are clamped into the sample holder, and a dough bubble is inflated. Figure is based on a figure in paper VI and illustrations in Chopin Technologies (2016).

It is also possible to assess the mixing properties of a flour on the alveograph apparatus by the consistograph method. In this method, the consistency of the dough is measured by a pressure sensor in the side of the alveograph mixing bowl (Dubois et al., 2008). A different mixer arm and a different geometry of the mixing bowl (compared to the mixing in the alveograph standard method) are used to increase the efficiency of the mixing (Dubois et al., 2008). This is also a standardised method (AACC, 2009b). The consistograph method is normally used to determine the water absorption of the flour to be able to adjust the water addition in the alveograph analysis and obtain a constant dough consistency (in contrast to the fixed water addition normally applied in alveograph analyses), but it can also be used to find other parameters, such as time to maximum consistency and tolerance (Dubois et al., 2008). In the standard method, flour is added to the mixing bowl, and a fixed amount of sodium chloride solution is added in the beginning of the mixing, after which the dough is mixed for 4 minutes. The maximum pressure during the mixing is used to calculate the water absorption of the flour. The analysis is subsequently repeated using the adjusted amount of water calculated from the flour water absorption and with a mixing time of 8 minutes. This is done to ensure that the maximum consistency of the dough is within the target range.

Parameters such as stability and time to obtain maximum pressure can also be found. Compared to the alveograph method, the consistograph method is rarely applied. Instead, other analysis methods such as farinograph or mixograph are often used for determination of mixing properties of flour.

The alveograph method is normally used for flour benchmarking. Multiple studies have therefore investigated how the results from the alveograph analysis is related to genetic diversity and cultivation environment (Bordes et al., 2008; Branlard et al., 2001; N. M. Edwards, Gianibelli, et al., 2007; N. M. Edwards, Preston, et al., 2007; Vázquez et al., 2012; Zanetti et al., 2001), as well as other flour analyses or product properties (Abuhammad et al., 2012; Addo et al., 1990; Bettge et al., 1989; Cappelli et al., 2018; Huen et al., 2018b; Ktenioudaki et al., 2011). Multiple studies have also used the alveograph to assess the effects of flour treatment and addition of other ingredients. This includes flour treatments such as milling conditions and thereby the content of damaged starch (Dexter et al., 1994; Preston et al., 1987) and defatting of flour (Addo & Pomeranz, 1992), as well as addition of ingredients including emulsifiers and lipids (Addo et al., 1995; Addo & Pomeranz, 1992; Agyare et al., 2005), reducing and oxidising agents (Bennett & Coppock, 1952), resistant starch (Barros et al., 2018), fibres (Mehfooz et al., 2018; J. Wang et al., 2002), gluten (Janssen et al., 1996; Li et al., 2013), enzymes (Li et al., 2013; Rosell et al., 2003) and yeast metabolites (Jayaram, Cuyvers, et al., 2014; Jayaram, Rezaei, et al., 2014). In most of the studies, the additives were tested one at a time. The alveograph method was also applied in paper V to analyse the effect of addition of α-, β- and γ-cyclodextrin. It was found that the cyclodextrins had multiple effects on the properties of wheat dough, which the alveograph parameters was used to quantify.

3.1. OVERVIEW OF ALVEOGRAPH CURVES AND PARAMETERS

Over the years, several different parameters have been extracted from the alveograph pressure curve. At first, these were often based on the curve characteristic, such as height, length and area under the curve (Chopin, 1927; Dubois et al., 2008). Later on, parameters were also found from the first derivative curve (Addo et al., 1990), and the pressure-air curve has been recalculated into a stress-strain curve from which additional parameters were found (Bloksma, 1957; Dobraszczyk et al., 2003; Launay & Buré, 1977). In total, ten parameters are provided for each analysis in the modern version of the alveograph. These parameters are maximum overpressure (P), average abscissa to rupture (L), swelling index (G), configuration ratio (P/L), deformation energy (W) and elasticity index (Ie) found from the pressure curve, as well as minimum and maximum of first derivative (Dmin and Dmax, respectively) from the first derivative curve, and strain hardening index (SH) and strength coefficient (K) from the stress-strain curve. In Figure 3-2, an overview is given of how the different alveograph parameters are extracted from the different curves. The different parameters are shortly described here, but a longer review of them can be found in paper II.

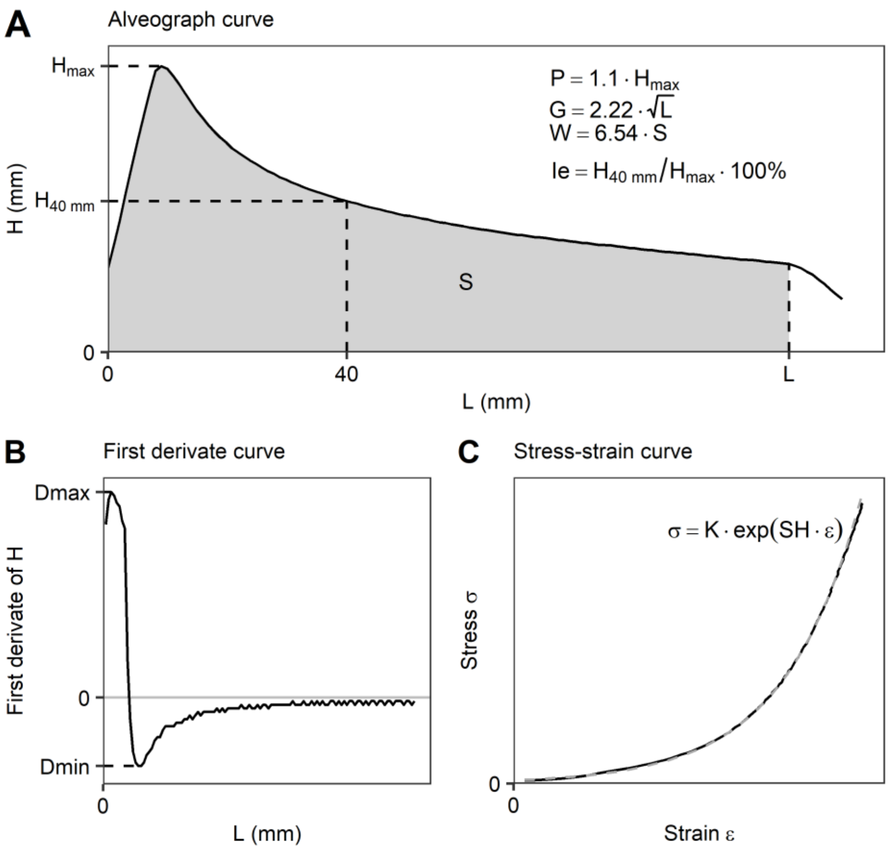

Figure 3-2: Alveograph parameters found from the different curves. A: The pressure curve from which P, L, G, W and Ie are found. Other formulas for calculation of G and W exist. S is the area under the curve, H_{max} is the maximum height of the curve, and $H_{40\ mm}$ is the height of the curve at 40 mm on the L axis. B: The first derivate curve from which Dmin and Dmax are found. C: The stress-strain curve from which SH and K are found. The figure is from paper II.

The pressure curve, which can be seen in Figure 3-2A, has L and H on the abscissa and the ordinate, respectively. They are both measured in mm, which originates from the design of the first versions of the alveograph, which was made approximately a century ago. The H axis represents the inflation pressure, and it can be recalculated into mm H_2O by multiplying it with a factor of 1.1. This conversion is necessary due to the geometry of the initially used water manometer. The scale on L axis can be recalculated into inflation time by a conversion factor of 5.5 mm/sec. In the older versions of the alveograph, the pressure was recorded on chart paper, and the conversion factor indicates therefore the speed of the recording drum. Despite the data are recorded on a computer nowadays, the resultant curve is as standard still presented using the original units on the axes.

The parameter P is the maximum overpressure needed to inflate the dough bubble (Dubois et al., 2008). It is found by multiplying the maximum height of the alveograph curve with 1.1, as P is measured in mm H_2O. P represents the dough tenacity, and it is considered to be an indicator of the dough resistance to deformation (AACC, 2009a), but many possible interpretations of it have been made over the years (Dubois et al., 2008). P has been shown to be related to the water absorption of the flour, as a higher water absorption of a flour result in a higher P value (Cappelli et al., 2018; Dexter et al., 1994; Preston et al., 1987). The water absorption is influenced by multiple variables, including starch damage level (related to the milling process) and pentosan level (especially in relation to wholemeal flour), and increasing the amount of each of these will increase the water absorption (Cauvain, 2015). Also strengthening of the gluten network by e.g. ascorbic acid has been shown to increase P (Bennett & Coppock, 1952; Kitissou, 1995). P does not seem to be significantly related to the protein content of the flour (Addo et al., 1990; Bettge et al., 1989; N. M. Edwards, Gianibelli, et al., 2007; Khattak et al., 1974; Rasper et al., 1986).

The parameter L is the average length of the curve from the start of inflation to the point where the dough bubble ruptures (Dubois et al., 2008). L is provided in mm, but it can be converted to time. It represents the biaxial extensibility of the dough. L is presumed to be related to the gluten network, as modifications of this have been shown to affect L (Bennett & Coppock, 1952; Janssen et al., 1996; Khattak et al., 1974; Li et al., 2013). Also, the water absorption of the flour influences L, as a stiffer dough is often less extensible (Cappelli et al., 2018; Dexter et al., 1994; Preston et al., 1987). L has been shown to be positively correlated with bread volume by several studies (Addo et al., 1990; Bettge et al., 1989; Dowell et al., 2008; N. M. Edwards, Preston, et al., 2007).

The parameter G is the swelling index. It is defined as the square root of the average volume of air in ml used for inflating the dough until rupture (Dubois et al., 2008). G is therefore another measure of the biaxial extensibility. Using the assumption that the dough bubble volume increases uniformly with time during the inflation, G can be calculated from L (Dubois et al., 2008). G can be calculated using the formula in equation (3-1) according to Bordes et al. (2008) and Cauvain & Young (2009), while Chopin Technologies (2016) mentions the formula in equation (3-2.

$$G = 2.226 \cdot \sqrt{L} \tag{3-1}$$

$$G = 2.22 \cdot \sqrt{L} \tag{3-2}$$

The further premises for the different formulas are unknown. As G is calculated from L, G is affected by the same variables as L.

The parameter W is the deformation energy, as it represent the energy needed for inflating the dough bubble until rupture (Dubois et al., 2008). W can be used as an indicator of strength of the flour. W is calculated from the area under the curve, as the

L and H axis can be converted to represent the bubble volume (i.e., the volume change from zero volume) and the pressure, respectively. The work for a gas is the product of pressure and volume change. In a case like the present in which the pressure is not constant, the product is replaced by an integral corresponding to the area under the curve. According to Dubois et al. (2008), Cauvain & Young (2009) and Rasper et al. (1986), W measured in 10^{-4} J can be found using the formula in equation (3-3, in which S is the area under the curve in cm^2, while Chopin Technologies (2016) mentions the formula in equation (3-4, in which V is the volume of air measured in ml.

$$W = 6.54 \cdot S \tag{3-3}$$

$$W = 1.32 \cdot \frac{V}{L} \cdot S \tag{3-4}$$

The further assumptions and intermediate calculations for the conversion of the axes for the two formulas are unknown. The W value is influenced by the values of P and L, as P and L are to some degree related to the area under the curve, from which W is found (Addo & Pomeranz, 1992; Bettge et al., 1989; N. M. Edwards, Gianibelli, et al., 2007). W is widely used industrially to assess the strength of wheat cultivars and flour qualities to indicate which types of bakery products they are suitable for (Abuhammad et al., 2012; García-Álvarez et al., 2011). W has been shown to be dependent on the amount and quality of gluten (N. M. Edwards, Gianibelli, et al., 2007; Janssen et al., 1996; Vázquez et al., 2012), as well as it is related to the water absorption of the flour (Dexter et al., 1994; Preston et al., 1987). Multiple studies have observed a positive correlation between W and bread volume (Addo et al., 1990; Bettge et al., 1989; Dowell et al., 2008; N. M. Edwards, Preston, et al., 2007).

The ratio P/L is called the configuration ratio. It is the ratio between the maximum overpressure and the average abscissa to rupture, and it thus indicates the balance between the tenacity and extensibility of the dough (Dubois et al., 2008). The value is dimensionless. P/L can be applied industrially together with W, but while the magnitude of W is used to assess the strength of the flour, P/L should often just be within a certain range (Bordes et al., 2008).

The parameter Ie is the elasticity index. Ie is the ratio between the height of the alveograph curve at 40 mm on the L axis and the maximum height of the curve, and it is stated in percentage (Kitissou, 1995). Ie is an indicator of dough elasticity according to Kitissou (1995), as it is assumed that at bubble volume at 40 mm on the L axis, the pressure is mainly dependent on the strength of the internal bonding forces and to a lesser degree the dough thickness. Ie is related to the gluten network quality of the dough, as strengthening of the gluten network has been shown to increase Ie, as well as to the water absorption of the flour (Kitissou, 1995). Duyvejonck et al. (2012) found a positive correlation between Ie and bread volume, but in general the use of Ie in the literature is limited.

The first derivative curve, which can be seen in Figure 3-2B, is found from the alveograph curve. The abscissa is therefore the same L axis as for the original curve, while the ordinate is the slope of a tangent line to the curve for each point.

The parameter Dmin is the minimum value on the first derivative curve, and it corresponds therefore to the steepest decreasing slope of the alveograph curve. The parameter was defined by Addo et al. (1990), however, they defined it as the negative of the minimum value in order to obtain a positive number. Addo et al. (1990) and Addo et al. (1991) found that Dmin was correlated with bread volume, but beside this very few studies have been published using Dmin.

The parameter Dmax is the maximum value on the first derivative curve, and it represents therefore the steepest increasing slope for the increasing pressure in the beginning of the alveograph curve. To the best of the author's knowledge, there is no mention of Dmax in the literature.

The alveograph curve has been transformed into a stress-strain curve using various assumptions, as an attempt to derive fundamental rheological properties of dough analysed with the alveograph method. Hlynka & Barth (1955) made an early attempt to calculate the stress-strain curve from the alveograph curve, using the assumption that the dough bubble is a sphere with a uniform wall thickness over the bubble surface for a given bubble volume. However, visual inspection of the dough bubble during inflation reveal that the dough is thinner in the pole compared to the base. Bloksma (1957) proposed that the dough wall thickness should be calculated under the assumptions that the dough bubble is spherical, the dough is incompressible, and each dough particle is shifted normally to itself during inflation. Using these assumptions, the size of the dough bubble and the dough wall thickness for different positions on the bubble can be calculated for different times during inflation. Launay et al. (1977) tested the validity of Bloksma's model and found that the model was only accurate at moderate volumes and flow rates, while the model was not accurate at the flow rate normally used in the alveograph analysis, because the height of the bubble was overestimated, as the bubble was oblate spheroidal instead of spherical. This was supported by Charalambides et al. (2002), who also found that that the thickness of the dough was underestimated at the pole and overestimated at the base of the bubble, and that the compressibility of the dough had a significant effect on the results. Nevertheless, Bloksma's model is widely used for calculation of the stress-strain curve for the pole of the bubble from the alveograph curve using equation (3-5 to (3-9.

$$V = \frac{\pi}{6} \cdot h \cdot (h^2 + 3a^2) = Q \cdot t \tag{3-5}$$

$$R = \frac{a^2 + h^2}{2h} \tag{3-6}$$

$$\Delta = \Delta_0 \left(1 + \frac{h^2}{a^2}\right)^{-2} \tag{3-7}$$

$$\varepsilon = \ln \left(1 + \frac{h^2}{a^2}\right) \tag{3-8}$$

$$\sigma = \frac{p \cdot R}{2\Delta} = \frac{p}{4} \cdot \frac{(a^2 + h^2)^3}{h \cdot \Delta_0 \cdot a^4} \tag{3-9}$$

In the equations, V is the volume of the dough bubble, h the bubble height, a the radius of the original dough sample, Q the air flow rate, t the time, R the bubble radius, Δ is the dough thickness at the pole, Δ_0 is the initial dough thickness, ε the Hencky strain, σ the stress, and p the overpressure in the bubble. For equation (3-5, it is assumed that the bubble volume increases with a constant rate. The stress and the strain for the pole of the dough bubble can be calculated from equation (3-8 and (3-9, respectively, as the variable h can be found from equation (3-5. The equations for calculation of the bubble radius and the dough thickness at the pole are also provided in equation (3-6 and (3-7, respectively, as they are used in the calculation of the stress. Assuming constant a, Q and Δ_0, it can be seen from the above equations that the calculated strain is only dependent on time, while the calculated stress is only dependent on time and pressure. However, the assumptions for the calculation have been shown not to hold at the conditions used in the standard alveograph analysis, which results in overestimation of the strain and especially the stress (Charalambides et al., 2002, 2006; Launay et al., 1977).

An example of the stress-strain curve can be seen in Figure 3-2C. The unit for the stress axis is unknown, as the curve is automatically calculated by the alveograph software, but no description of how it is done and which units that are applied is available from the manufacturer. Personal communication with Chopin Technologies indicates that an erroneous factor is used for the calculation of the stress in the stress-strain curve in the alveograph software, which influences the values on the vertical axis, but not the shape of the curve. This will be corrected in coming versions of the alveograph software. A curvature on the stress-strain curve can be observed, which is presumed to be caused by strain hardening (Dobraszczyk & Roberts, 1994). The exponential equation in equation (3-10 was found to be suitable for fitting the curve (Dobraszczyk et al., 2003).

$$\sigma = K \cdot \exp(SH \cdot \varepsilon) \tag{3-10}$$

In the equation, σ is the stress, ε the Hencky strain, SH the strain hardening index and K the strength coefficient.

Strain hardening is the phenomenon that the stress required to deform a material increases more than proportionally to the strain (at increasing strain and constant strain rate) (van Vliet et al., 1992). The strain hardening index can be found for uniaxial or biaxial extension, but differences in the obtained indexes can be observed between the different extension types (Sliwinski et al., 2004b). Determination of the strain hardening index by different methods may also result in different values due to inaccurate determination of strain and stress, different and variable strain rates, as well as use of different equations for fitting. When comparing different strain hardening indexes from different studies, it is therefore important to pay attention to the methods used.

In the alveograph method a constant air flow is used for the bubble inflation, which entails that the strain rate at the pole of the bubble decreases during inflation (Charalambides et al., 2002). However, the deformation properties of the dough, including the strain hardening index, are also dependent on the strain rate, as it is well known that dough exhibits strain hardening as well as strain rate hardening (Dobraszczyk, 2004a; Launay & Buré, 1977). For this reason, and because the calculated stress and strain are overestimated (Charalambides et al., 2002, 2006; Launay et al., 1977) resulting in a too high SH, SH found from alveograph analysis is only the apparent strain hardening index.

Many of the studies which determine SH for dough by bubble inflation do not use an alveograph, but a D/R Dough Inflation System (Stable Micro Systems, Surrey, England) (Dobraszczyk, 1997). This is based on the same principle as the alveograph, but different analysis conditions are applied, as the bubble inflation is often performed using an approximate constant strain rate of 0.1 s^{-1} (Dobraszczyk et al., 2003). Furthermore, there are some differences in the sample preparation. Chin et al. (2005) have compared bubble inflation at (approximate) constant strain rate and constant flow rate, and they found that the type of deformation rate influences SH, which therefore entails that the results are not directly comparable.

Strain hardening of a dough is assumed to be related to the gluten network, as polymer entanglement network theory can be used to explain the phenomenon by entanglement coupling of large glutenin molecules (Dobraszczyk & Morgenstern, 2003; Singh & MacRitchie, 2001). Multiple studies have also shown that SH is dependent on the gluten network properties (Altuna et al., 2016; Chin & Campbell, 2005b; Sroan et al., 2009). SH have also been shown to be positively correlated with bread volume by several studies (Dobraszczyk et al., 2003; Dobraszczyk & Salmanowicz, 2008; Sroan et al., 2009). van Vliet et al. (1992) stated that locally increasing resistance to deformation due to strain hardening entailed that the gas cells in the dough could be inflated to larger volumes and with thinner cell walls before the dough ruptured, which eventually lead to larger bread volume.

The parameter K is the strength coefficient. It is found from equation (3-10, in which K indicates the intercept with the ordinate. K estimates therefore the stress when the strain equals 0. As described previously, different challenges are linked to the calculation of strain and stress, which also affect the value of K. Different studies have tried to relate K with flour quality, but the results are ambiguous (Chin et al., 2005; Chin & Campbell, 2005b; Tronsmo, Magnus, et al., 2003).

3.2. COMPARISON OF PARAMETERS

In paper II it was investigated which of the alveograph parameters that are closely related using correlation analysis. If the correlation coefficient between two parameters was close to 1, this would indicate that the parameters to a large extent represented the same information. Some of the findings from paper II are presented in this section. The data used for the correlation analysis were the parameter values extracted from the alveograph curves from a number of alveograph analyses. The results from these analyses were also used in paper III, IV and V. In these studies, many of the alveograph analyses were performed differently than prescribed by the standard method (AACC, 2009a). For some analyses, different additives, including cyclodextrins or all ingredients for either bread dough or Danish pastry dough was added, the water content of the dough was varied, different mixing times were applied, and/or the analyses were conducted at lower analysis temperatures than standard. Only three different flour qualities were analysed. These alveograph analyses were therefore performed differently compared to what the alveograph method is normally used for. Nevertheless, these data were used for the correlation analysis, as they covered a wide range of values for each parameter. They were therefore assessed to be suitable for studying the integral relationships between the parameters. Scatter plots between the alveograph parameters were also made, which can be seen in Figure 3-3. Clouds or clusters can be seen between some of the parameters. Further investigation of the scatter plot (see supplementary materials in paper II) reveal that these clusters partly originate from different dough compositions (different ingredients added to the dough) and to a lesser extent different flour qualities.

The correlation coefficients between the alveograph parameters can be seen in Table 3-1. Very high correlation coefficients were observed between some of the parameters, including L and G (r = 0.99), P and Dmax (r = 0.98), P and K (r = 0.98), Dmax and K (r = 0.98), as well as Ie and SH (r = 0.97). G is calculated from L, which explains the very strong correlation between them. The square root of L is used for the calculation of G, which is why the correlation coefficient is not 1, as this is based on linear relationships. The very strong correlations between the parameters P, K and Dmax might be explained by they are all related to the dough behaviour in the beginning of the bubble inflation, as P is the maximum overpressure in the first part of the pressure curve, Dmax is the steepest slope for the increasing pressure in the alveograph curve, and K estimates the stress at low strain. The very high correlation coefficient between Ie and SH might be explained by both parameters assess curve shapes, as Ie and SH are extracted from the alveograph curve and the stress-strain curve, respectively. As the parameters G, Dmax, SH and K had very high correlation coefficients with other parameters, these four parameters did not provide much information not already provided by the remaining parameters.

Table 3-1: Pearson correlation coefficients between the alveograph parameters (n = 532). All correlations were significant with a p-value < 0.01. The table is from paper II.

	P	L	G	W	P/L	Ie	Dmin	Dmax	SH
L	-0.74								
G	-0.74	0.99							
W	0.76	-0.25	-0.22						
P/L	0.87	-0.85	-0.88	0.39					
Ie	0.57	-0.24	-0.23	0.81	0.36				
Dmin	-0.85	0.71	0.70	-0.49	-0.79	-0.11			
Dmax	0.98	-0.74	-0.73	0.78	0.83	0.59	-0.85		
SH	0.62	-0.28	-0.28	0.76	0.46	0.97	-0.17	0.61	
K	0.98	-0.76	-0.75	0.72	0.85	0.46	-0.91	0.98	0.49

Remaining were the parameters P, L, W, P/L, Ie and Dmin, which represent a basic set of parameters for characterisation of the alveograph curve. G, Dmax, SH and K, which were closely correlated with P, L and Ie, could also be applied, however, the most used parameters for the alveograph analysis were selected here. Strong correlations could be found between some of the remaining parameters, some of which are described in the following.

A negative, moderately strong correlation between P and L was found. Similar findings were reported by some studies (Bettge et al., 1989; Zanetti et al., 2001), while other studies did not find significant correlations between these parameters (Addo et al., 1990; Bordes et al., 2008; N. M. Edwards, Gianibelli, et al., 2007; García-Álvarez et al., 2011). The correlation might originate from only few flour qualities being analysed, even though these were treated in different ways. Previous studies have shown that when changes in dough composition resulted in a stiffer dough, which was seen as a higher P value, the dough was often also less extensible, observed by a smaller L value (Cappelli et al., 2018; Jayaram, Cuyvers, et al., 2014; Preston et al., 1987).

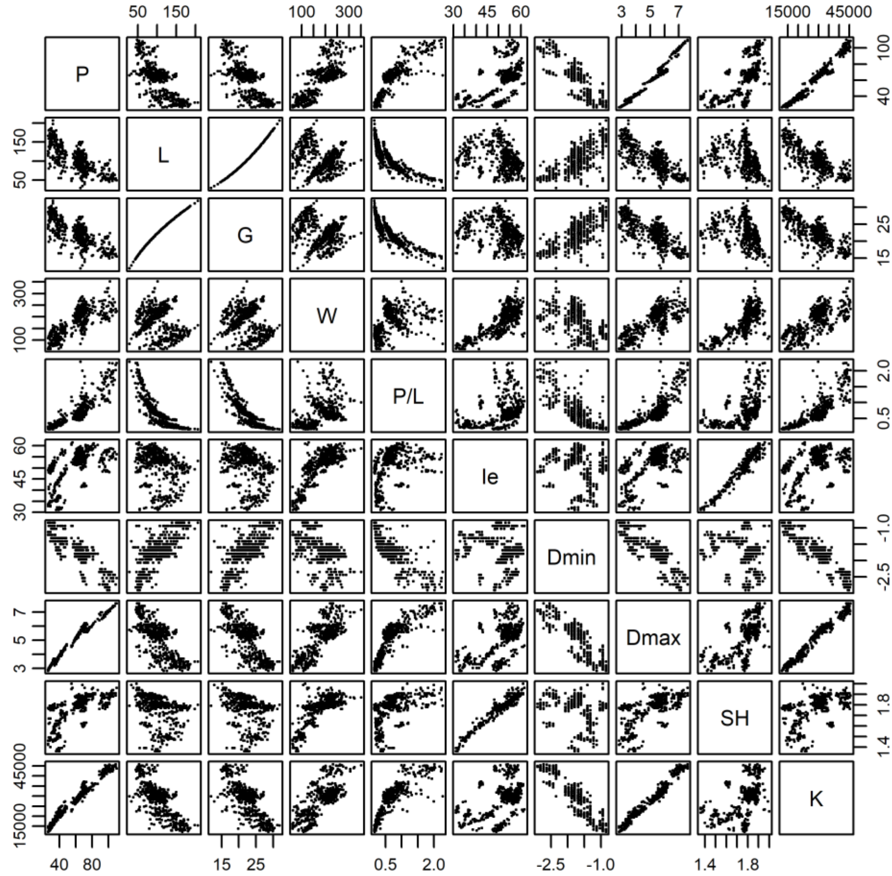

Figure 3-3: Scatter plot matrix between the different alveograph parameters. The figure is from paper II.

A positive, moderately strong correlation between P and W was also observed, which was also found by multiple other studies (Addo et al., 1990; Bettge et al., 1989; N. M. Edwards, Gianibelli, et al., 2007; García-Álvarez et al., 2011; Zanetti et al., 2001). This was also expected as P is calculated from the maximum height of the alveograph curve, which to some extent is related to the area under the curve, from which W is calculated. On the other hand, a weak negative correlation was observed between L and W, despite L represents the length of the curve and therefore is also partly related positively to the area under the curve and thereby W. A positive correlation between L and W was also found by multiple other studies (Addo et al., 1990; Bettge et al., 1989; N. M. Edwards, Gianibelli, et al., 2007; García-Álvarez et al., 2011; Zanetti et al., 2001). However, in the scatter plot between L and W in Figure 3-3, several clusters were observed, and investigation of these together with the correlation coefficients between L and W for the different dough composition, revealed that a positive correlation between L and W could be found for the different dough compositions. Ie was positively correlated with W, which was also observed or at least indicated in several other studies (Bordes et al., 2008; Duyvejonck et al., 2012; Huen et al., 2018b; Zanetti et al., 2001).

P/L was positively correlated with P and negatively correlated with L, which was also expected. It is clear from the scatter plots in Figure 3-3, the correlation was not linear, which is because P/L is the ratio between the two parameters, and it will therefore be more affected by changes at high P values and low L values.

Moderately strong correlations between Dmin and the other parameters, such as P, L and W, were also observed. Dmin is rarely used in the literature, but Addo et al. (1990) found significant, moderately strong correlations between Dmin and the other alveograph parameters. Compared to those results, some of the same correlations could be found, while other correlations were different, which might be due to Addo et al. (1990) compared different flour qualities, while different dough compositions were also compared in the study.

All the alveograph parameters are found from curves which are only based on two variables, namely inflation time (or more specifically, amount of air) and pressure. The parameters are therefore to some degree related to each other. The characteristics of the alveograph curve are dependent on a number of variables, including the properties of the flour, the water content in the dough and whether ingredients are added. Changes in these variables will change the characteristics of the alveograph curve, which will often affect several parameters. However, it is different to what extent the parameters are affected by changing variables. The alveograph parameters are therefore to some degree interlinked, but the further details of the relationships between them are diffuse at best.

CHAPTER 4. ANALYSIS OF FULL FORMULA DOUGH

Within the baking industry, it is strongly presumed that the rheology of a dough, which is traditionally assessed by kneading and stretching the dough by hand, is closely related to its baking quality (Dobraszczyk, 2004b). Empirical evidence over the years has strengthened this assumption (Dobraszczyk, 2004b). Rheology can be used to determine how the dough behaviour is affected by deformation of the dough, e.g. during mechanical handling, such as mixing and sheeting, and during bubble growth in fermentation and baking (Cauvain, 2015). Although the importance of dough rheology is widely accepted, measurements on the rheology of full formula dough are usually not applied in the industrial bakeries. Multiple reasons can be found for this as covered previously, but often the physical and often empirical descriptive analysis methods are focused on flour characterisation, as flour is assumed to be one of the most important ingredients, and the variability of the flour is pivotal for the product quality (Li Vigni et al., 2009; Spies, 1990).

4.1. INFLUENCE OF INGREDIENTS ON BREADMAKING AND DOUGH PROPERTIES

Multiple studies have investigated the correlation between flour characteristics and product properties, usually bread volume. Strong correlations have been observed between rheological properties of simple flour doughs and bread volume, as shown in the following examples. Bettge et al. (1989) found correlations between loaf volume and alveograph extensibility (L) with correlation coefficients of 0.85 and 0.90 for soft (n = 58) and hard (n = 15) wheat flours, respectively. Dobraszczyk & Salmanowicz (2008) found a correlation coefficient of 0.88 between bread volume and failure strain in bubble inflation (n = 31). Duyvejonck et al. (2012) found bread volume to be correlated with both alveograph elasticity index (Ie) and deformation energy (W) with correlations coefficients of 0.80 and 0.72, respectively (n = 19). Tronsmo, Færgestad, et al. (2003) found a correlation coefficient of 0.89 between bread volume and strain hardening index determined using bubble inflation for hearth breads (n = 20).

In some of the studies reporting high correlation coefficients, prediction models were made for prediction of bread volume. However, the prediction value of these models was often limited, as the prediction interval based on the standard error typically covered large parts of the bread volume range (Andersson et al., 1994; Ktenioudaki et al., 2011; Stojceska & Butler, 2012). F. C. Wang & Sun (2002) found a correlation coefficient of 0.94 between creep recovery strain and loaf volume (n = 23), but when Stojceska & Butler (2012) calculated the 95% prediction interval for the loaf volume, they found the prediction interval was approximately 90 ml, while the overall variation in the loaf volume in the study was approximately 200 ml. Likewise, Ktenioudaki et al. (2011) found a correlation coefficient of 0.8 between uniaxial extensibility and loaf volume (n = 9), but the 95% prediction interval for the loaf volume was 18 ml, while the overall variation in the loaf volume was approximately 24 ml. This shows that strong correlations do not necessarily result in good prediction models and emphasises the importance of considering the standard error.

Furthermore, some studies did not find any correlation between rheological properties and bread volume. Huen et al. (2018a) did not find any significant correlations between results from a range of physical analysis methods and specific bread volume (n = 37), despite the applied analysis methods had resulted in significant correlations with bread volume in other studies. Tronsmo, Færgestad, et al. (2003) only found a significant correlation coefficient to bread volume, when hearth breads were made, while no significant correlations to the volume of loaves made using the Chorleywood bread process were observed.

The flour analyses are therefore only indicative of the breadmaking performance of a flour for a given set of conditions. There are various reasons for this, some of which also have been mentioned previously. One of these reasons is that the analyses are conducted at ranges of deformation and strain rate that are not representative for the deformation conditions of dough in the breadmaking process (Dobraszczyk & Morgenstern, 2003). The measured response is therefore not likely to be directly related to baking performance (Dobraszczyk & Morgenstern, 2003). Multiple recipes and procedures for breadmaking are also used in the different studies, which further complicates the comparisons, as different breadmaking procedures might lead to different results for the same flour samples as shown by Tronsmo, Færgestad, et al. (2003). The protein content of the flours used in the studies should also be considered, as e.g. flours with a protein content lower than what is normally applied for breadmaking will result in a smaller bread volume, and if these are included in the study, this will affect the regression analysis (Stojceska & Butler, 2012).

In most studies, including those mentioned above, only the relations between the flour properties and the properties of the final product are investigated. The rheological properties of dough are often measured, but the measurement is usually performed on a simplified dough containing only flour, water and possibly sodium chloride. However, the doughs used to produce the breads for assessment of baking performance contain also other ingredients, e.g. yeast, fat, sugar and enzymes. In general, the processability or the properties of full formula dough is rarely investigated, including how this is related to the ingredient properties or the quality of the final product, despite the general assumption that the rheology of the dough is determining for the baking performance (Dobraszczyk, 2004b).

The use of different ingredients in a dough for a bakery product affects the properties of the dough, including the rheology and the baking performance. The effects of the ingredient are of course dependent on the type of ingredient and the amount of it, as well as which other ingredients are added. The effects of some of the various ingredients found in Danish pastry predough are briefly described in the following. Focus is on the effects on mixing and dough deformation properties, even though most of the ingredients also affect other properties and the quality of the final product.

It is generally accepted that flour is one of the most vital ingredients for dough rheology and product properties (Spies, 1990). Flour is quantitatively the most important ingredient in bread, and it has been shown that the variability of the flour among all the ingredients is the most determining factor for the bread quality in an industrial production (Li Vigni et al., 2009). The properties of flour are dependent on both the genetics of the wheat and the growing conditions as well as the milling conditions and the degree of refining of the flour (Bordes et al., 2008; Cappelli et al., 2018; Preston et al., 1987; Vázquez et al., 2012). The mixing properties of a dough are found by measuring the dough consistency during mixing (Goesaert et al., 2005). The overall shape of the mixing curve is caused by changes in the flour constituents during mixing, including flour hydration, gluten network development and gluten protein depolymerisation. Other ingredients might affect the characteristics of the mixing curve as indicated by e.g. maximum consistency, dough development time and stability. A strong flour typically results in long dough development time and stability (Cauvain, 2015). The maximum dough consistency during mixing of a dough consisting of flour and water can be used to determine the water absorption of the flour. The water absorption is dependent on the content of pentosans, protein, damaged starch and moisture in the flour (Cauvain, 2015). The flour constituent with largest influence of the dough rheology is generally accepted to be the gluten proteins (Goesaert et al., 2005). Gluten proteins can be divided into gliadin and glutenin, and the amount and type of gliadin and glutenin as well as the ratio between them have been shown to have a large influence on the dough properties. For example, a negative correlation has been found between the gliadin/glutenin ratio and the dough development time (Barak et al., 2013). Modifications of the gluten network such as addition of gluten as well as strengthening or weakening of the gluten network by addition of oxidising and reducing agents, respectively, have also been shown to affect the extensional properties of the dough (Bennett & Coppock, 1952; Janssen et al., 1996; Kitissou, 1995; Li et al., 2013). Also the content of other flour constituents affect the dough properties, as some of these bind water, which is needed for development of the gluten network, and this might affect the behaviour of the gluten network (Cappelli et al., 2018; Preston et al., 1987).

Water is essential for the properties of the dough, and it is one of the most determining ingredients for the rheology of the dough. Water hydrates the flour constituents, of which it is associated with especially starch, proteins and pentosans (Cauvain, 2015). Water molecules can therefore be found in several different states in the dough (Schiraldi & Fessas, 2012). The hydration of the gluten proteins is necessary for the formation of the gluten network, and too little water in a dough may limit the development of the gluten network. Increasing water content has been shown to decrease the consistency of the dough (Berland & Launay, 1995; Farahnaky & Hill, 2007; Jekle & Becker, 2011). The softening effect of the water is caused by the plasticizing effect of the water molecules, as water prompts the gluten polymers to shift from a rubbery stage to a flow stage, and at the same time, the entanglements in the gluten network disappear due to slippage (according to the polymer entanglement network theory) (Jekle & Becker, 2012). It has been found that water primarily has a diluting effect and does not cause major structural changes (Berland & Launay, 1995; Meerts et al., 2017). In alveograph analyses, increasing water addition has been shown to decrease the tenacity P, increase the extensibility L (followed by a decrease), decrease the deformation energy W and decrease the configuration ratio P/L (Cappelli et al., 2018; Preston et al., 1987). In uniaxial extension, increasing water addition has been shown to decrease the maximum resistance in extension, while the extensibility increases (Jekle & Becker, 2012). Furthermore, increasing water content in the dough has been found to increase the stickiness of the dough (Jekle & Becker, 2011, 2012).

Bakers' yeast (*Saccharomyces cerevisiae*) is widely used in bakery products, in which its main function is to serve as a leavening agent, while it also contributes to the flavour and other properties of the final product. The yeast is active in the dough, and the effects of yeast are therefore dependent on time. The activity of the yeast is also influenced by other ingredients, such as sugar and sodium chloride (Cauvain, 2015). The yeast releases different metabolites, including CO_2, ethanol, succinic acid, acetic acid and glycerol, of which CO_2 primary accounts for the volume expansion during fermentation (Meerts, Ramirez Cervera, et al., 2018). In general, CO_2 in combination with the other yeast metabolites have been found to have a softening effect of the dough during fermentation (Meerts, Vaes, et al., 2018). The effects of the yeast metabolites have also been studied individually. Ethanol in the amounts produced by yeast during fermentation has been shown to lower the extensional viscosity and reduce failure strain, which has been proposed to be due to solubilisation of gliadins, which limits the number of non-covalent interactions in the gluten network (Meerts, Ramirez Cervera, et al., 2018). This was supported by Jayaram, Rezaei, et al. (2014), who observed ethanol decreased the extensibility and total force for deformation in extensograph and alveograph analyses. However, while the results presented by Meerts, Ramirez Cervera, et al. (2018) indicated that ethanol softened the dough, Jayaram, Rezaei, et al. (2014) found that that ethanol turned the dough stiffer, as addition of ethanol increased the maximum resistance to deformation of the dough. Ethanol did not seem to influence the mixing properties of dough (Jayaram, Rezaei, et al., 2014). Succinic acid did not show an effect on the measured dough properties at the concentrations normally produced by yeast, while use of higher concentrations of succinic acid were found to soften the dough, lower the extensional viscosity and reduce the failure strain (Meerts, Ramirez Cervera, et al., 2018). Succinic acid has been shown to decrease the dough development time and the stability time, as well as reduce the extensibility of the dough in the extensograph analysis, and also increase the tenacity and reduce the extensibility in the alveograph analysis (Jayaram, Cuyvers, et al., 2014). However, the effect of succinic acid is highly dependent on pH and salt concentration, and contradictory results are therefore often found (Jayaram, Cuyvers, et al., 2014). Succinic acid was found to be the primary reason for the pH drop in the dough during fermentation (Jayaram et al., 2013). Glycerol has been shown to soften the dough, but not cause major structural changes (Meerts, Ramirez Cervera, et al., 2018). Aslankoohi et al. (2015) found that glycerol increased the extensibility and decreased the maximum resistance to deformation, which is consistent with softening of the dough. In the above-mentioned studies, the effects of the yeast metabolites were studied by addition of the components to the dough. However, when the rheological properties of unfermented and fermented dough were compared, the differences were smaller than what might be expected (at least for the applied methods) when comparing them with the effects observed for addition of the individual yeast metabolites to the dough (Meerts, Ramirez Cervera, et al., 2018). This might be because the yeast metabolites are gradually produced in an already-developed gluten network during fermentation, and they may therefore not influence the development of the gluten network to the extent otherwise found (Meerts, Ramirez Cervera, et al., 2018). Furthermore, the yeast might also during fermentation produce other components, which affect the dough rheology, e.g. enzymes (Meerts, Ramirez Cervera, et al., 2018). In addition to the above-mentioned yeast metabolites, which are primarily present in fermented dough, yeast also contains glutathione. Glutathione is released from dead yeast cells, and it is therefore also found in yeasted, unfermented dough (Verheyen et al., 2015). Glutathione is a reducing agent, and it is considered to interrupt the formation of disulphide bonds in the gluten network (Verheyen et al., 2015). In mixing analysis, glutathione has been shown to decrease dough development time and stability time and increase the softening of the dough (Verheyen et al., 2015), as well as decrease the dough consistency (Berland & Launay, 1995). Glutathione has been found to decrease the resistance to deformation and increase the extensibility in deformation studies (Kieffer et al., 1990; Meerts, Ramirez Cervera, et al., 2018).

Egg has a range of different functions in the dough as well as in the final product. Egg has been shown to increase the dough development time, as well as the dough strength and stability, while it decreases the water absorption (Calderón-Domínguez et al., 2005; Indrani & Venkateswara Rao, 2007; Van Steertegem et al., 2013). Analysis of egg yolk and egg white separately revealed that egg white increased development time, strength and stability (more than whole egg), while egg yolk decreased these parameters (Van Steertegem et al., 2013). The effects of egg are assumed to be caused by interactions between egg proteins and glutenin proteins, as the negatively charged egg proteins (especially found in the egg white) partly shield the positively charged glutenin and gliadin proteins, which strengthen the interactions between the glutenin chains (Van Steertegem et al., 2013). Egg has also been shown in extensograph analysis to increase the ratio of maximum resistance to deformation and extensibility, which is caused by higher maximum resistance and/or lower extensibility, and to increase the area under the curve, indicating strengthening of the dough (Indrani & Venkateswara Rao, 2007).

Sugar is added to sweeten the bakery product as well as to function as an energy source for the yeast. Addition of sucrose to dough is usually associated with increased stickiness, lower tenacity and higher extensibility (Cauvain, 2015; A. Salvador et al., 2006). Sucrose is considered to bind water, which reduces the availability of water for hydration of gluten proteins, resulting in a less consistent dough and a longer development time (Calderón-Domínguez et al., 2005; Meerts, Vaes, et al., 2018). Sucrose has been found to lower the dough consistency, but without inducing major structural changes, as it was shown that the effect of sucrose was due to volume changes of the dough (Meerts, Vaes, et al., 2018; A. Salvador et al., 2006). Sugar increases the activity of the yeast, however, if the concentration is too high, it will inhibit the yeast (Sahin et al., 2019).

In-dough fat, such as margarine and shortening, has different effects dependent on the type and concentration. The fat affects a range of properties in both the dough and the final product (Pareyt et al., 2011). Fat is presumed to interfere with the formation of the gluten network (Ghotra et al., 2002). Fat has been shown to reduce the amount of water needed to reach a fixed dough consistency (Pareyt et al., 2011). This has been suggested to be due to coating of the gluten proteins and starch granules (Chin et al., 2010). Fat exerts a plasticizing effect on the viscoelastic properties of the dough, possibly by reducing the concentration of entanglements and crosslinks in the gluten network (Fu et al., 1997; Mehta et al., 2009).

Sodium chloride is important for the taste of the product, as well as it affects the dough rheology and the activity of the yeast. Sodium chloride has been shown to increase the dough development time, as well as the dough stability and strength (Butow et al., 2002; Calderón-Domínguez et al., 2005; Indrani & Venkateswara Rao, 2007; Van Steertegem et al., 2013; Wehrle et al., 1997). Furthermore, sodium chloride decreases the dough consistency (Farahnaky & Hill, 2007; Wehrle et al., 1997). Salt has been observed to increase the resistance to deformation when the dough is extended, while ambiguous results were observed for extensibility (Lynch et al., 2009). It is generally accepted that sodium chloride electrostatically shields some of the charged amino acids at the surface of the gluten proteins, which then allows the proteins to interact more closely in hydrophobic interactions (McCann & Day, 2013). This strengthens the dough and decreases the hydration rate of the flour (McCann & Day, 2013). Furthermore, salt interacts with water, and thereby possibly reduce the hydration rate of the flour proteins due to competition for the water (Calderón-Domínguez et al., 2005).

Ascorbic acid is widely used as a flour improver, as it (or actually the oxidized form dehydroascorbic acid) functions as an oxidizing agent and therefore is able to modify the gluten network (Grosch & Wieser, 1999; I. Lucas et al., 2018). The exact mechanism of ascorbic acid is unclear, but it is presumed to function by oxidizing glutathione (Koehler, 2003). This results in stiffening and strengthening of the dough (Dong & Hoseney, 1995). Accordingly, addition of ascorbic acid has been shown to increase the resistance to deformation and decrease the extensibility of the dough in uniaxial extension analysis (Kieffer et al., 1990), as well as increase the tenacity and decrease the extensibility as measured by alveograph analysis (Bennett & Coppock, 1952).

Hydrocolloids, including pectin and taragum, can also be added to bakery products. Hydrocolloids have various chemical structures and properties, and different effects of the hydrocolloids on the dough have therefore been observed, dependent on e.g. how and which flour constituents the hydrocolloids interact with (Rosell et al., 2007). Hydrocolloids affect both the dough, pasting and product properties (Bollaín & Collar, 2004; Rosell et al., 2007).

A range of different enzymes might also be added to the dough. Dependent on the type of enzyme, the enzymes affect different flour constituents and in different parts of the breadmaking process. One of the enzymes, which catalyses reactions with starch, is α-amylase. This enzyme is also one of the most frequently used enzymes in the baking industry (Cauvain, 2015). α-amylase is endo-acting and hydrolyses α-1,4 linkages in starch (Cauvain, 2015; Goesaert, Slade, et al., 2009). It thereby degrades starch into oligosaccharides, which can be further hydrolysed by β-amylase, which is naturally present in the flour (Cauvain, 2015; Goesaert, Slade, et al., 2009). The amylase has several functions, including promotion of yeast fermentation by increasing the amount of fermentable sugars, increment of bread volume by reducing the dough viscosity during starch gelatinisation, improvement of crust colour by Maillard reactions promoted by the production of reducing sugars, and in some cases inhibition of staling by affecting the starch network (Goesaert, Leman, et al., 2009; Goesaert, Slade, et al., 2009). Other baking enzymes, such as xylanase, hydrolyse non-starch polysaccharides. Xylanase hydrolyses arabinoxylans, which have a large water-holding capacity. When parts of the arabinoxylans in the flour are degraded by xylanase, some of this water can be released and instead be used for hydration of the gluten network (Hardt et al., 2014). Addition of xylanases are associated with decreasing consistency of the dough (Ingelbrecht et al., 2000) and softening of the dough (Hardt et al., 2014). When xylanases are used in appropriate amounts, it is related to increased bread volume and better crumb structure (Cauvain, 2015). Enzymes that react with proteins are also applied in the baking industry. This includes transglutaminase, which strengthens the gluten network in the dough by crosslinking of proteins. Transglutaminase affects the rheology of the dough and can also increase the loaf volume and affect the crumb texture (Caballero et al., 2007), when used in appropriate concentrations (Joye et al., 2009). Furthermore, transglutaminase has been shown to increase pastry lift, possibly because the integrity of the layers is better preserved with the stronger gluten network (Gerrard et al., 2000).

The effect of an ingredient is of course dependent on the type of ingredient and the amount of it. Furthermore, synergistic and antagonistic effects have been observed between different ingredients (Bollaín & Collar, 2004; Calderón-Domínguez et al., 2005; Rosell et al., 2007). In many studies, the effects of only one or a few ingredients are tested (Agyare et al., 2005; Ananingsih et al., 2013; McCann & Day, 2013; Van Steertegem et al., 2013). It is therefore not possible to estimate interaction effects in these studies. In other studies, in which several ingredients are tested, the type and amount of ingredients are often selected using a specific type of bakery product as a starting point in order to limit the number of ingredients tested (Calderón-Domínguez et al., 2005; Indrani & Venkateswara Rao, 2007; Perego et al., 2007). Furthermore, in many of the aforementioned studies only one type of flour was used, making it hard to estimate the effects of the ingredients on other flour qualities.

In order to assess the effects of the flour as well as the other ingredients, analysis of full formula dough must be applied. Only a few studies have been published that analyse doughs with all ingredients for a bakery product. These studies have investigated different properties, including mixing properties (Alava et al., 2001; Calderón-Domínguez et al., 2005; Oliver & Allen, 1992; Wesley et al., 1998) and deformation properties (Casutt et al., 1984; de la Horra et al., 2015; Rezaei et al., 2016; Tlapale-Valdivia et al., 2010; Vanin et al., 2018; Verheyen et al., 2014). Several challenges are related to analysis of yeasted dough, as the time-dependent effects of yeast must be considered (Rezaei et al., 2016; Verheyen et al., 2014).

Most of the above-mentioned studies which assessed the deformation properties of yeasted dough applied uniaxial extension. Few studies have attempted to analyse full formula dough by biaxial extension using bubble inflation. Uniaxial and biaxial extension have however been shown to result in different rheological vales due to orientation of the gluten polymers (Sliwinski et al., 2004a). Bennett & Coppock (1956) attempted to use a modified protocol for analysis of yeasted doughs on the alveograph, but they found this to result in unsatisfactory results, most likely due to the incorporation of a 3-hour rest period. Some studies have used the D/R Dough Inflation System (Dobraszczyk, 1997), but no considerations regarding the time-dependent effects of yeast were mentioned in the studies (Altuna et al., 2016; Ananingsih et al., 2013; Dobraszczyk, 1997). Some studies such as Dobraszczyk & Morgenstern (2003) state that biaxial extension by bubble inflation has several advantages compared to uniaxial extension, e.g. biaxial extension is thought to resemble the conditions experienced by the dough cell walls and is therefore assumed to be more relevant for assessment of breadmaking performance.

4.2. ADJUSTED ALVEOGRAPH PROTOCOL FOR ANALYSIS OF DANISH PASTRY DOUGH

Dough with all ingredients for a bakery product was analysed by biaxial extension using the alveograph. As the standard alveograph protocol is designed for flour analysis, modifications of the protocol were made before full formula dough was analysed. Different types of full formula were also analysed with this protocol, including Danish pastry predough, which in the following is referred to as Danish pastry dough. The new protocol for alveograph analysis of full formula dough was presented in paper III. This protocol was also used in paper IV and VI to analyse different types of full formula doughs. In paper III, the protocol was used to analyse dough with all ingredients for Danish pastry dough mixed in the alveograph and samples of Danish pastry dough from an industrial production at different mixing times, while flour-water dough (which is used as standard) was analysed using the standard protocol. Some of the findings in paper III are presented in this section. In paper IV, bread dough and Danish pastry dough made from three different flour qualities were analysed using the adjusted protocol, as well as the flours were analysed with the standard protocol. In paper VI, different samples of industrial Danish pastry dough were analysed and compared.

The new alveograph protocol was adjusted compared to the standard protocol described in AACC method 54-30.02 (AACC, 2009a). These adjustments were made, as it was observed that if full formula Danish pastry dough was analysed using the standard protocol, the foam structure in the dough became too distinct. This resulted in irregular rupture of dough bubbles during inflation, causing large random variation and thereby unusable results. The distinct foam structure was assessed to be due to the activity of the yeast, as the yeast produces CO_2, which increases the volume of the air bubbles in the dough (van der Sman & van der Goot, 2009). The alveograph protocol had to be able to analyse dough samples from an industrial production, and it was therefore not a possibility to leave out the yeast in the dough. Furthermore, it is well known that yeast has several effects on the properties of the dough, also before fermentation, which could not be assessed if the yeast was left out (Meerts, Ramirez Cervera, et al., 2018). To reduce the yeast activity to a level at which no notable effects of the yeast were observed during the analysis, the dough temperature in the analysis was therefore lowered. No procedures for inactivation of the yeast were included, and the yeast was therefore active during the analysis. Unwanted variability in the results from yeast activity was diminished by treating the samples in the same way and conducting the bubble inflations within a short time range after the resting step. Together with the reduction of the yeast activity by lowering the analysis temperature, this was sufficient to obtain reproducible results.

The Danish pastry dough samples from the industrial production were collected after the mixing but before the lamination, and therefore before fat was folded into the dough. The samples were frozen after they were extracted, as they were stored and transported before analysis. For logistic reasons, it was not possible to analyse the dough samples directly after extraction. Before freezing, the samples were rolled out, so they all had the same thickness, to ensure similar freezing and thawing conditions for all the samples. The dough samples were already mixed, but they were mixed again in the alveograph before extrusion to homogenise the dough, remove possibly incorporated air bubbles and increase the dough temperature. Danish pastry dough is in general undermixed, in order to allow further dough development during lamination and rolling processes, and it was therefore possible to further mix the dough without risk of extensive overmixing.

The temperatures during the analysis was reduced to limit the activity of the yeast. Some of the ingredients were cooled before mixing, including the flour, which was stored at -18 °C (room temperature as standard), and ice-cooled water was used (20 °C as standard). The samples from the industrial production were thawed at 5 °C before analysis. The temperature was also lowered in the alveograph for the different analysis steps, as the mixing bowl was 18 °C (24 °C as standard), the resting chamber 18 °C (25 °C as standard) and the test chamber 15 °C (20 °C as standard).

Temperature is important for multiple properties of the dough. The mixing properties of the dough are influenced by the temperature, as increasing mixing temperature has been shown to decrease the dough consistency, development time and stability (Başaran & Göçmen, 2003; Farahnaky & Hill, 2007; Rosell & Collar, 2009). The temperature influences also the type of protein network interactions formed during mixing, as Quayson et al. (2016) found that at low mixing temperature noncovalent interactions appear to drive protein network formation, while covalent interactions dominate at higher temperatures. The dough deformation properties are also dependent on the temperature. Increasing mixing temperature has been shown to decrease the maximum resistance and the area under the curve, but the results are also dependent on the dough development stage (Başaran & Göçmen, 2003; Calderón-Domínguez et al., 2004).

Mixing is an important step, and multiple processes occur during mixing, including development of gluten network, redistribution of starch granules and water, and incorporation of air (Schiedt et al., 2013). The development of the dough is therefore decisive for the properties of the dough. The dough development is affected by multiple variables, including flour properties, other ingredients and mixing conditions (Ooms & Delcour, 2019), as shown above. In the standard alveograph method, the flour and sodium chloride solution are mixed for 8 minutes, which results in a dough suitable for analysis. However, in the adjusted protocol, multiple variables, which are known to affect the dough development, are changed, e.g. temperature and addition of ingredients. Various mixing times were therefore applied in paper III to investigate the effect on the properties of dough. A few examples of the alveograph curves for some of the mixing times can be seen in Figure 4-1. Additional alveograph curves can be seen in the figures in paper III.

When the flour-water dough was analysed using the standard analysis protocol after different mixing times, it was observed that the curves in general were similar. However, for the shortest mixing times minor differences in height and length of the curves were seen. The characteristics of the curves did not seem to be dependent on the extrusion order.

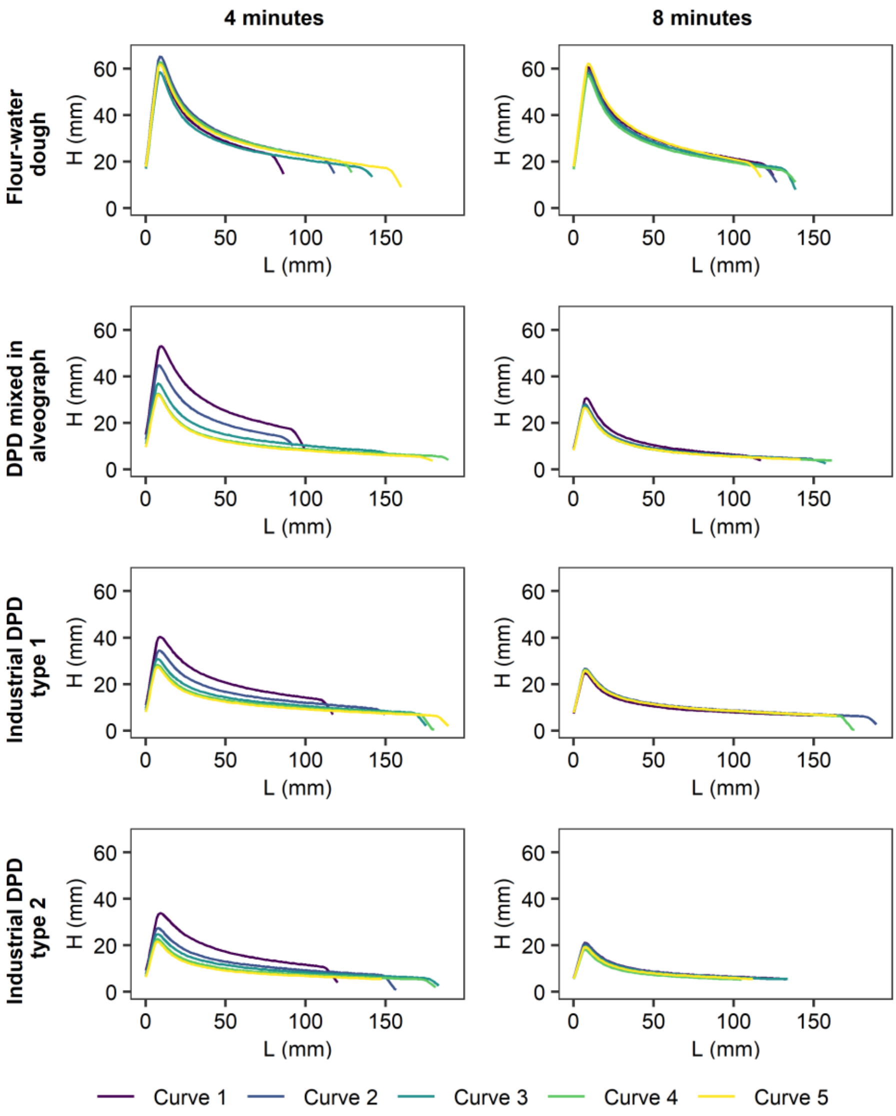

Figure 4-1: Examples of alveograph curves of different dough types, including flour-water dough, Danish pastry dough (DPD) mixed in the alveograph and two types of industrial Danish pastry dough measured after mixing times of 4 minutes and 8 minutes. The curve numbers indicate the order, in which the dough pieces were extruded, 1 being the first and 5 the last. Some of the curves are from figures in paper III.

Different Danish pastry doughs were analysed using the adjusted alveograph protocol and different mixing times. Danish pastry dough was made by placing all the ingredients in the alveograph mixer, except water, which was added automatically in the beginning of the mixing. Two types of Danish pastry dough used for plait products were also sampled from the industrial production. All three types of Danish pastry dough contained almost the same ingredients, while there were some differences in the origin as well as minor differences in the recipe, e.g. in the water content. The two types of industrial samples were sampled at different days, and different batches of the ingredients were therefore used.

For the Danish pastry doughs, large variability could be seen between the curves for the shorter mixing times, but the variability decreased with longer mixing times, and at the longest mixing times the curves were similar. Furthermore, the height and the length of the curves seemed to depend on the extrusion order, as the curve was in general higher and shorter for the first extruded dough piece than for the last. This tendency was most pronounced at the shorter mixing times and for the curve height. The changes in height and length of the curves were presumed to be caused by the additional mixing the dough experienced during extrusion, as this also was consistent with the curves in general became lower and longer for increasing mixing times. The curves were similar at the longer mixing times, indicating that the dough at this development stage did not change that much during extrusion. In some of the curves for the longer mixing times, no abrupt decrease in the pressure could be observed, indicating that the bubble inflation was terminated before the dough bubble burst. This happened due to an error in the alveograph software, and it especially occurred if the pressure was low. The different tendencies were found at different mixing times dependent on the type of Danish pastry dough. In general, these tendencies occurred at shorter mixing times for the industrial dough samples compared to the dough mixed in the alveograph, which was expected as these doughs were premixed. Nevertheless, differences could also be observed between the two types of industrial dough samples.

In the standard analysis, an average curve of the five curves is used for the determination of the alveograph parameters. For the standard analysis the curves are similar and close to each other, as seen for flour-water dough with a mixing time of 8 minutes in Figure 4-1, and it is therefore acceptable to use an average curve. When the adjusted alveograph protocol was applied, larger variability was observed between the curves, and it was therefore necessary to analyse the results differently. The parameters were therefore determined for the individual curves, making it possible to calculate the mean and the standard deviation for each replicate. The values for the different mixing times were plotted for the parameters tenacity (P), biaxial extensibility (L), deformation energy (W) and elasticity index (Ie), see Figure 4-2. For the flour-water dough, the parameter values depended only little on the mixing time. On the other hand, the parameters values for the Danish pastry doughs were very dependent on mixing time. The values of the parameters P, W and Ie decreased with increasing mixing time, while L increased and subsequently decreased. However, it should be noted that L and W might be underestimated for the Danish pastry doughs at the longer mixing times due to premature stop of inflation, as L and W are found from the length of the curve and the area under the curve, respectively.

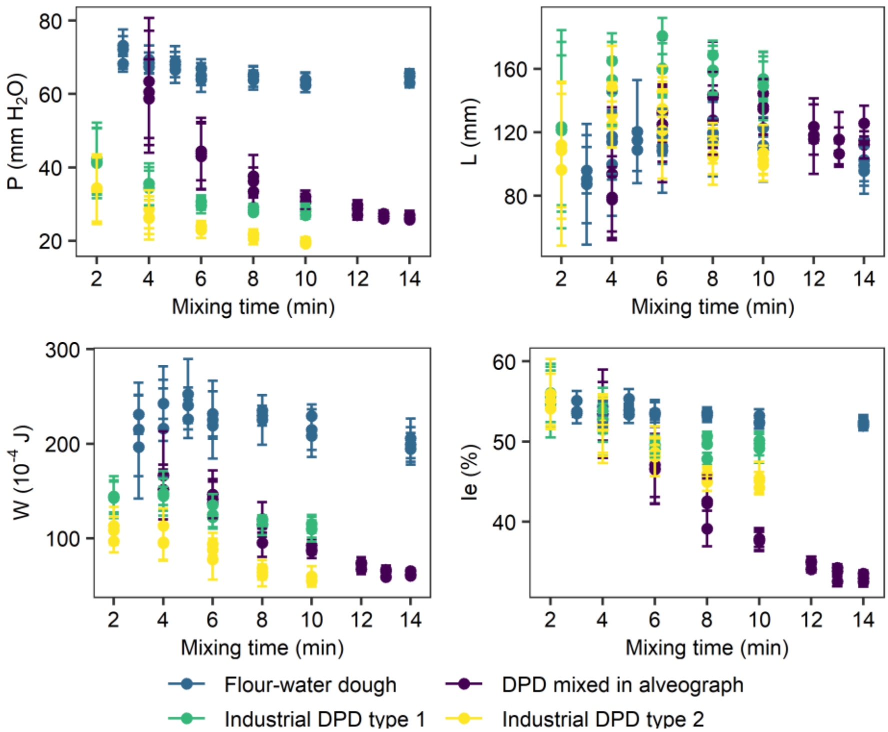

Figure 4-2: Mean and standard deviation for each replicate of the alveograph parameters dough tenacity (P), dough biaxial extensibility (L), deformation energy (W) and elasticity index (Ie) for the flour-water dough, the Danish pastry dough (DPD) mixed in the alveograph and the two types of industrial Danish pastry dough at different mixing times. The figure is from paper III.

The standard deviations for the parameters in Figure 4-2 seemed to decrease with longer mixing times until a certain level. Different mixing times were needed in order to achieve this level, dependent on the dough type. The standard deviation represents the variability among the five curves and comprises therefore both the variability caused by the dough development during the extrusion and the random variation between the curves. The smaller standard deviations observed at longer mixing times seemed to be caused by a decrease on the variability caused by dough development during extrusion. The magnitude of the standard deviation might therefore indicate the dough development stage.

When the alveograph results were compared to the dough consistency curves from the mixing, it was also observed that the large variability between the curves was related to the dough development. If the dough was extruded before optimal dough development (which is the maximum consistency during mixing), the characteristics of the individual alveograph curves were dependent on the extrusion order, while if the dough was extruded when it was optimally mixed or at a later stage, the variability between the curves seemed to be due to random variation, indicating that the dough development during extrusion did not affect or only to a small degree affected the characteristics of the curves.

When the standard deviations for the different parameters and dough types were compared, it was found that standard deviations in approximately the same range as for the standard analysis (flour-water dough mixed in 8 minutes) could be obtained for the Danish pastry doughs. For the Danish pastry dough mixed in the alveograph, this was obtained with a mixing time of 10 minutes, and for the industrial samples of Danish pastry doughs with a mixing time of 6 minutes.

The development of the adjusted protocol opens for alveograph analysis of full formula dough. When applying the adjusted protocol, the handling of the dough must be considered, as the samples must be treated as similar as possible, and extensive yeast activity should be avoided. Furthermore, the mixing time must be taken into consideration. It might not be feasible to characterise the dough for a range of different mixing times, as this would increase the workload substantially compared to the standard analysis protocol. One mixing time could therefore be chosen, possibly after a screening of different mixing times. The mixing time is important for the obtained results, as the values of the alveograph parameters for the Danish pastry dough were more dependent on mixing time compared to flour-water dough as shown in Figure 4-2. The mixing time should be adjusted according to the dough type, as the curve characteristics of undermixed dough might depend on the extrusion order, while extensively overmixed dough becomes sticky and difficult to handle. Dough consistency curves from mixing may be used as support in the selection of mixing time.

Application of the adjusted alveograph protocol may include testing of different additives in a dough which contains all ingredients for a bakery product, and it is therefore also possible to observe interactions between the additives. It may also be used to assess the effect of different processes or evaluate the dough properties at different positions on a production line.

It should be noted that the results from different dough types should not be compared if they are not handled in the same way and analysed using the same protocol. It is therefore not possible to compare the results from the different dough types described above, except for the two industrial dough samples, as it is not possible to know which variables (dough compositions, handling or analysis conditions) the differences could be assigned to.

In section 3.1, it is described how the alveograph parameters are found, and what they are known to be related to for the standard analysis. The parameters are found in the same way when the adjusted alveograph protocol is applied. However, it is unknown whether the relations between alveograph parameters and final product properties still are valid, as the relations were found for simple flour-water dough, while full formula doughs were analysed using the adjusted protocol.

4.3. EFFECT OF DIFFERENT DOUGH TYPES AND FLOUR QUALITIES

The adjusted alveograph protocol was used in paper IV to assess the effect of different flour types on the dough properties for different types of dough. Some of the findings in paper IV are presented in this section. The three flour types represented different flour qualities intended for different bakery products, as they were normally used for Danish pastry, buns and cake. The three flour types were analysed as flour-water dough using the standard alveograph protocol and as bread dough and Danish pastry dough using the adjusted protocol. Only one mixing time was applied for each dough type. The flour-water doughs were mixed for 8 minutes, as the standard protocol prescribes, while the bread doughs and the Danish pastry doughs were mixed for 10 minutes, as this was found to result in a dough suitable for analysis. Furthermore, it was shown in paper III that when the Danish pastry dough was analysed after a mixing time of 10 minutes, then the standard deviations for the different alveograph parameters calculated from the five alveograph curves for each replicate were approximately in the same range as the standard deviations in the standard analysis. Similar results were observed for the bread doughs. Beside the alveograph analysis, the doughs were also analysed using consistography to obtain a mixing curve. For the consistograph analysis of the different dough types, the same temperature as in the alveograph mixing bowl for the alveograph analysis was used. Furthermore, additional flour analyses were made, and the breadmaking performance was assessed by measuring the bread volume.

The results for the consistograph and alveograph analyses can be seen in Figure 4-3 and Figure 4-4, respectively. The bubble inflation stopped prematurely in some of the alveograph analyses, as it also was observed in paper III, causing in a potential underestimation of L and W. This was detected for one and two flour types for bread dough and Danish pastry dough, respectively, and it is indicated in Figure 4-4.

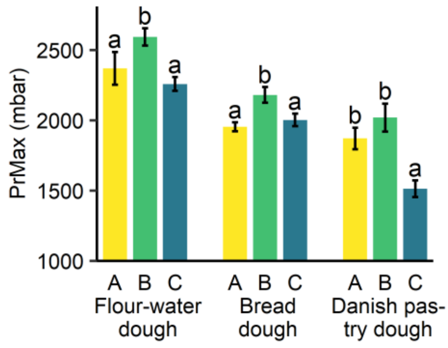

Figure 4-3: Consistograph results from analysis of different flour types for different dough types. Wheat flour intended for Danish pastry (Type A), buns (Type B) and cake (Type C) were analysed. The flour-water dough comprised only of flour, water and sodium chloride, while the bread dough contained flour, water, sodium chloride and yeast, and the Danish pastry dough contained flour, water, egg, sugar, yeast, margarine, improver and sodium chloride. Different analysis temperatures were applied for the flour-water dough and the full formula doughs. PrMax is the maximum pressure during mixing, representing the maximum dough consistency. The error bars indicate the standard deviation. For each type of dough, columns with the same lower-case letter are not significantly different ($P < 0.05$). The figure is from paper IV.

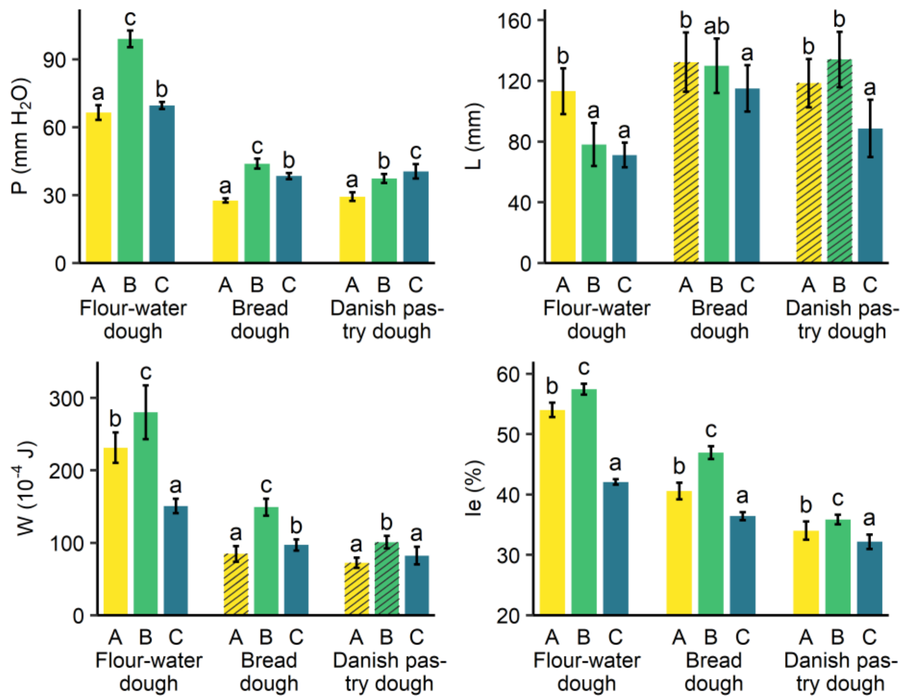

Figure 4-4: Alveograph results from analysis of different flour types for different dough types. Description of the different flour types and dough types can be seen in the caption for Figure

4-3. Different analysis conditions were applied for the flour-water dough and the full formula doughs. The results for the parameters dough tenacity (P), dough biaxial extensibility (L), deformation energy (W) and elasticity index (Ie) are shown. The hatched columns indicate that the value might be underestimated due to premature stop of inflation. The error bars indicate the standard deviation. For each type of dough, columns with the same lower-case letter are not significantly different ($P < 0.05$). The figure is from paper IV.

The rankings of the flour types were compared between the different dough types, as the doughs were made using different compositions and analysed using different protocols. Due to these differences, it would not be possible to assign changes in the dough properties to specific variables, and therefore comparison of rankings was chosen instead of direct comparisons of the results from different doughs. The bread dough and Danish pastry dough were both analysed using the same protocol, but there were major differences in the dough compositions, including in the water content and the type of ingredients. The rankings of the flour types were for many parameters the same among the different types of dough, but differences could also be found. For the parameter P, a different rank order of the flour types could be observed when the flour-water dough and the Danish pastry dough were compared. Also changes in whether or not two flour samples were significant different between the dough types could be observed for some of the parameters. I.e. two flour types were significant different, when one dough type was analysed, and not significant different for another dough type. This was the case for e.g. the parameter PrMax, when the results for flour-water dough and Danish pastry dough were compared.

These variations in rankings and in differences being significant or not can be due to multiple reasons, including differences in the analysis conditions and the dough compositions. Differences could also be observed between bread dough and Danish pastry dough, which were analysed using the same protocol, indicating that variations in analysis conditions were not the sole reason for differences in the results. The dough properties are dependent on both the properties of the flour and the other ingredients as shown in section 4.1, but the effect of both flour quality and other ingredients are rarely studied at the same time. The results in Figure 4-3 and Figure 4-4 indicate that the effects of addition of ingredients are dependent on the flour type. To assess the effects of and interactions between the flour and the other ingredients in ratios representative for bakery products, analysis of full formula dough can therefore be applied.

In paper IV, fixed water addition and mixing time were applied regardless of the flour water absorption and the dough development time. However, these parameters would normally be adapted in bread production according to the properties of flour and the type of dough. The results from paper III underlined also that the mixing time influenced the alveograph parameters for the Danish pastry dough, while the mixing time in the standard analysis of flour-water dough seemed to have a smaller effect. Future work might therefore investigate how the results are affected, when the water addition and the mixing time are adjusted.

When the results from the consistograph and alveograph analysis were compared with the bread volumes from the different flour types, no unambiguous relations between the analysis results and the bread volume were found. This was possibly caused by too few flour types were analysed. Future work could further investigate the relationships between the properties of the full formula dough and the final product, as strong correlations between alveograph parameters and bread volume found for the standard analysis do not necessarily apply when full formula dough is analysed.

4.4. APPLICATION OF THE ADJUSTED ALVEOGRAPH PROTOCOL FOR CHARACTERICATION OF INDUSTRIAL DOUGHS

The adjusted alveograph protocol was used to analyse different types of full formula dough. This included doughs made by mixing the ingredients in the alveograph, as well as frozen dough samples from an industrial Danish pastry production. In addition to the analysis results of dough samples from paper III presented above, other industrial Danish pastry dough samples were also analysed. Some of these results can be seen in paper VI and are presented in the following.

The adjusted alveograph protocol was used to compare dough samples with different dough recipes, and differences in the resultant parameters could be revealed. Industrial dough samples with and without pastry trimmings added to the ingredients before mixing were also analysed. Pastry trimmings are not available at the beginning of the production, and margarine is therefore added to the dough instead. It was not possible to measure any difference between the samples by the adjusted alveograph protocol, despite the operators at the production line stating that it was possible to feel a difference. There might be multiple reasons for that, e.g. adjustments of the dough recipe regularly were made in the industrial production dependent on whether the dough contained pastry trimmings or not to counteract the different behaviour of the doughs later in the process. The sample preparation with freezing and thawing of the dough might also have led to differences in the dough properties that could not be measured.

It was also attempted to assess the dough properties at different positions on the industrial Danish pastry production line using the adjusted alveograph protocol. The dough was laminated without margarine, as the additional mixing in the alveograph before extrusion and bubble inflation would destroy the layered structure, and the addition of margarine would change the properties of the dough. Assessment of dough development at different positions was achieved but did not lead to any useful conclusions, as the implementation of margarine in the lamination turned out to be more important for the development of the dough than initially assumed. At the same time, our measurements indicated that the application of dusting flour decreased the water content of the dough, which affected the dough consistency. The adjusted alveograph protocol makes it possible to assess some effect of different recipes in the industrial production, while further improvements are needed in order to analyse other process variables.

The adjusted alveograph protocol is able to analyse the deformation properties of unfermented full formula dough. The dough can either be made by addition of all ingredients to the alveograph mixing chamber or be sampled from e.g. an industrial production. Analysis of full formula dough by the adjusted alveograph protocol makes it possible to assess the effects of the ingredients. Although analysis of full formula dough would be assumed to be more closely related to the final product compared to the standard analysis, the dough is analysed shortly after mixing with this protocol. The effect of other breadmaking processes, such as shaping, fermentation and baking, are therefore not assessed, even though they are also important for the properties of the final product. The dough is mixed in the alveograph, but this mixing might not be representative for the conditions at the large scale production, as a range of different variables in relation to mixing affect the dough (Cauvain, 2015). These variables include the type of mixer, the mixing speed, the work input, the mixing temperature and the incorporation of air (Chin & Campbell, 2005b; Ktenioudaki et al., 2010; Quayson et al., 2016). The effect of some ingredients on the dough may only be observed at a later stage in the process, if they require time or heat before they become effective. Even though many variables in relation to the properties of the final product are not evaluated with the adjusted alveograph protocol, it can be used to assess the influence of more variables than the standard method, as analysis of full formula dough would be assumed to be more closely related to the final product compared with analysis of simple flour-water dough.

CHAPTER 5. POTENTIALS OF KNOWLEDGE-BASED AND DATA-DRIVEN DEVELOPMENT IN THE BAKING INDUSTRY

In paper VI, the potentials of using the adjusted alveograph analysis protocol and other dough characterisation methods in the industrial bakery production were assessed. The assessment involved the aspects of manufacturing high-variety products and adopting mass customisation, especially related to the fundamental capability robust process design. Some of the findings of paper VI are presented in this chapter. It was found that in order to obtain a manufacturing system for high-variety production, the current product development and production system in the Danish pastry production in Lantmännen Unibake Denmark were not suitable. Today, they are to some extent based on trial and error, tacit knowledge and experience, resulting in long time to market, changeover times and ramp-up times. This makes reducing batch size due to increasing variety unfavourable. Instead, more knowledge on the relations between the properties of ingredients, processes and products as well as industrial applicable dough characterisation methods are needed. Analysis of full formula, yeasted dough in the bakery industry is therefore one of the first steps in order to obtain a more robust and flexible manufacturing system.

To obtain the desired product quality and to reduce waste of materials and time, two topics are relevant in the industrial bakery production. More knowledge must be acquired of how raw materials, surrounding conditions, production processes and final products are related to each other, including how variability should be handled to obtain products with the desired quality (Ulrici et al., 2008). Furthermore, deviations from the production specifications must be detected as early in the process as possible in order to respond to the deviations (Ulrici et al., 2008). Analysis of full formula dough can be relevant in relation to both topics, as this can be used to test the effect of different variables and thereby obtain a higher level of understanding of the process, as well as it can be used for controlling the dough during production.

The mechanisms of the bakery production processes as well as the relations between the variables in ingredients, production processes and products are to some extent already known. In general, flour is considered to be the most important ingredient, but the product quality can in most cases not be predicted from the flour properties alone (Huen et al., 2018a; Ktenioudaki et al., 2011; Stojceska & Butler, 2012). Other ingredients and the interactions between them are also determining for the dough properties (Calderón-Domínguez et al., 2005; Meerts, Ramirez Cervera, et al., 2018;

Pareyt et al., 2011; Rosell et al., 2007; A. Salvador et al., 2006), as well as the flour quality result in different the dough properties dependent on the addition of other ingredients, as shown in in paper IV. Dough processing and especially mixing influence also the properties of the dough and final product, and several mixing variables, such as mixer design, mixing speed, energy input and temperature, are determining (Cauvain, 2015; Ktenioudaki et al., 2010; Wesley et al., 1998). Likewise, variables in fermentation and baking such as temperature and humidity are also essential for the properties of the final product (Cauvain, 2015).

In the bakery industry, many variables such as ingredient requirements and production processes are standardised. Despite standardisation of ingredient requirements, Li Vigni et al. (2009) found for an industrial bun production that the flour variability had significant impact on the product quality, while the variability of other main ingredients did not have a significant effect. The variability of ingredients besides flour may nevertheless be significant in the production of other bakery products. Multiple process variables are related to the product properties, and the variability of the process may therefore also significantly affect the product quality. Many process variables are adjusted by the operators during production based on their manual assessment of the dough. This is partly due to the limited range of analysis methods appropriate for industrial dough monitoring (Dobraszczyk & Morgenstern, 2003; Ulrici et al., 2008). Several of the most applied analysis methods used in relation to the cereal industry are aimed at flour characterisation, and they do therefore not assess the effect of the other ingredients nor the process variables and have thus limited value in the bakeries (Cauvain, 2015). Furthermore, most of the analysis methods are time-consuming and must be conducted by trained operators (Cauvain & Young, 2009), which reduces the possibility of early detection of deviations from the production specifications.

To obtain a manufacturing system for high-variety production, improvements must be made both in the understanding of the effects of different variables and in dough analysis methods. More knowledge of the relations and interactions between the ingredients, process and product must be obtained in order to establish a model that can predict the behaviour in the different processing steps. Optimally, it would be possible to predict the properties of the dough and the final product based on analysis of suitable ingredient properties and the surrounding environment together with the settings of the production processes and possibly control measurements of the dough during production using online data collection. However, more research is needed before this is possible. More focus on the dough behaviour and processability is also necessary, as this is often assessed manually in the industry, and measurements of dough behaviour are essential for early detection of deviations. Furthermore, collection of more relevant data in the industry is vital both in the product development and in the production system, before efficient high-variety production can be obtained. This includes analysis methods as well as collection and analysis of data. In product development, analysis methods can be used to obtain objective measures of the effect of e.g. different ingredients. This can also be used to study the relations between the different processes and variables as well as to generate knowledge for the prediction model. In the production systems, data monitoring can be used for process control to detect deviations from the production specifications. This might also be used for automatic adjustments of the process variables, if the response for different deviations is defined.

Depending on the purpose, different analysis methods will be relevant. Both chemical and physical properties of the dough can be analysed, and both empirical and fundamental methods are available. In order to generate new knowledge and study relationships, it can be reasonable to use certain analysis methods, even if they require long analysis time and manual handling. These methods may however not be suitable for process control in the production system. Furthermore, different methods are necessary to study different processes and variables. For instance, the adjusted alveograph protocol can be used to assess the effect of different ingredients and possibly processing steps on the extensional properties of unfermented dough, as shown in paper III, IV and VI. The adjusted alveograph can therefore be used for characterisation of yeasted dough before fermentation. Other measurement methods are relevant to study other variables and parts of the process, such as fermentation and baking.

For the purpose of process control in the production system, on-line or at-line measurements are usually more suitable than the abovementioned methods. Different methods may be relevant for different parts of the manufacturing system. Today, the most common collection of data in the breadmaking production is the dough divider, which controls the weight of the dough due to legal requirements (Cauvain, 2015). Image analysis can be used for quality control to evaluate e.g. the dimensions and the colour of the final product, and multiple commercial systems for this exist today (Cauvain, 2015; Li Vigni et al., 2009, 2013). Other process data, such as ingredient records, deliberate changes to the recipe or the process settings, and measurements of dough temperature, are available in many manufacturing systems and can also be logged (Cauvain, 2015). These data can be used to obtain a better understanding of the production system, but the data must be recorded and analysed to provide value (Bech, Brunoe, & Nielsen, 2019). The mixing process represents a large potential for process control, as some commercial mixers can record the mixing curves (Cauvain, 2015). These mixing curves are however rarely analysed, despite the importance of the mixing for the dough properties (Cauvain, 2015). Mixing is usually conducted for a fixed time or energy, but further analysis of mixing curves may e.g. be used to mix the dough to optimal dough development (Cauvain, 2015). Attempts have also been made to measure roll forces and dough sheet thickness in relation to sheeting in order to assess the dough rheology and quality, but this seems only to have been tested in laboratory-scale (Chakrabarti-Bell et al., 2010, 2017; Salimi Khorshidi et al., 2018). Near infrared spectroscopy (NIR) sensors have also shown promising results for process control in the bakery industry, as near infrared spectroscopy has been used in relation to flour (Li Vigni et al., 2009), mixing (Alava et al., 2001; Kaddour & Cuq, 2011; Wesley et al., 1998), fermentation (Ulrici et al., 2008) and baking (Thorvaldsson & Skjoldebrand, 1998). NIR sensors can be used to monitor physical and chemical changes of the dough that occur during the production processes, as the recorded absorbances in the spectrum are directly related to dough components, such as water, proteins and starch (Alava et al., 2001; Kaddour & Cuq, 2011). The measurements are non-invasive and can be performed at-line or on-line (Kaddour & Cuq, 2011; Ulrici et al., 2008). However, complex chemometric analysis is required before the results can be interpreted. NIR sensors might therefore be used for process control, but determination of the underlying reasons for the changes in the spectrums might be difficult (Alava et al., 2001; Li Vigni et al., 2009; Ulrici et al., 2008). Other examples of process control measurement methods for dough can also be found, e.g. ultrasound (Ross et al., 2004; Salazar et al., 2002) and the puff device (Morren et al., 2015).

Several different measurement methods are thus available and can be used for different purposes and in different parts of the manufacturing system. To obtain a better predictability and to respond to the challenges that increased variety entail in the production, it is essential to implement such measurement methods and to obtain a larger knowledge of the process. This will also contribute to decision-making based on knowledge and quantitative measurements, rather than personal assessments alone.

CHAPTER 6. CONCLUSION

The focus of this thesis has been on process understanding and assessment of the effect of variables in an industrial production of Danish pastry. The approaches for handling industrial process variables were therefore elucidated, and the challenges in obtaining robust production processes in relation to adopting mass customisation were identified. In order to analyse full formula dough, an adjusted protocol for alveograph analysis was made. This adjusted protocol was used to study the effect of ingredients on the dough properties, as well as it was attempted to assess the effect of process variables by the adjusted protocol. The potentials of implementation of knowledge-based and data-driven decision-making in the bakery industry were also addressed.

In the industrial bakery production, as exemplified by the manufacturing of Danish pastry at Lantmännen Unibake Denmark, the product development and adjustments of the production processes were to some extent characterised by a craft approach, and tacit knowledge and experience were used to handle process variables. This caused various challenges that are incompatible with high-variety manufacturing and adopting mass customisation. It was found that in order to overcome these challenges, the production system must be more robust. Cereal science is complex and involves many variables, and not all effects of dough constituents and processes are fully understood. However, the knowledge is constantly increasing, and a fair understanding of many of the variables has been achieved today. This knowledge has not been fully utilised in the baking industry due to multiple reasons, including the available analysis methods may not be suitable for use in the industrial production. Quantitative measurements of dough at the industrial production are necessary in order to obtain more robust production processes.

The alveograph method was used to measure biaxial extensional properties of dough. Linear correlation coefficients between the ten alveograph parameters, which are found from the bubble inflation curve or derivatives of it for every analysis, revealed that the parameters G, Dmax, SH and K were almost perfectly correlated with other parameters ($r \geq 0.97$). These four parameters contained thus very little information not already covered by the other parameters. The remaining parameters P, L, W, P/L, Ie and Dmin represent a basic set of parameters for characterisation of various parts of the alveograph curve. Less strong correlations could also be found between some of these, possibly reflecting that they were extracted from the same set of data and therefore to some extent interlinked.

An alveograph protocol for analysis of full formula dough was made in order to analyse full formula dough, including dough samples from the industrial production. Compared to the standard protocol, the analysis temperature was reduced, the mixing time had to be determined depending on the dough type, and the parameters were found from the individual pressure curves and not the average curve. A protocol for sampling and handling of industrial dough samples was also made to ensure uniform treatment of the samples. The dough temperature was reduced by multiple actions during the analysis in order to limit the activity of the yeast, as extensive yeast activity caused irregular bubble ruptures. The dough development was affected by the additional ingredients and the temperature changes, and the mixing time had thus to be determined for each dough type. The effect of mixing time was underlined by the parameter values were considerably more dependent on the mixing time for full formula Danish pastry dough compared to the flour-water dough. It was also observed that the characteristics of the alveograph curves were dependent on the extrusion order for short mixing times of full formula dough, as the curves became lower and longer the later the dough piece was extruded. The average curve should consequently not be used for determination of the alveograph parameters, and the parameters were therefore extracted from the curves for each dough piece. The standard deviation of the alveograph parameters extracted from the individual curves could be used to indicate the degree of systematic change in the curve characteristics, and this was found to be related to the dough development. Standard deviation of the alveograph parameters for the full formula doughs in the same range as found for the standard flour analysis protocol could be obtained after a mixing time of 6-10 minutes depending on the dough type.

The effects of different flour qualities on the properties of flour-water dough and two full formula doughs were assessed by the adjusted alveograph protocol. The rankings and the significant differences of the parameters between the flour types were different for the different dough types. This indicated that effects of the ingredients on the dough properties were dependent on the flour qualities. Analysis of flour-water dough is therefore not enough to predict the behaviour of the full formula dough, although it might give indications of it.

Multiple Danish pastry dough samples from the industrial production were also analysed using the adjusted alveograph protocol. It was found that the protocol could differentiate between doughs with different dough recipe, while the effects of other variables, such as addition of pastry trimmings to the dough, could not be detected. It was also attempted to assess the dough development at different stages of the industrial production, however without success. The adjusted alveograph protocol might therefore be used to assess the effect of some variables in the industrial production, while other analysis methods must be used for other variables.

With the adjusted alveograph protocol, the biaxial extensional properties of full formula, unfermented dough can be measured, and it can therefore be used for dough samples from an industrial production. In order to analyse full formula dough by the adjusted protocol, it is important that the samples are treated as similarly as possible, extensive yeast activity is avoided, and the mixing time is determined for each dough type. This protocol can thereby assess a range of variables in the industrial production of bakery products, which are normally not measured. Not all variables can be analysed by this protocol, for which reason other analysis methods are necessary to study the dough at other processing stages.

In order to obtain more robust production processes, analysis of dough in the industrial production is essential to obtain more knowledge on the relations between ingredients, processes and products. This is required to obtain a higher degree of predictability and to handle variability to maintain the desired product quality. Better and earlier detection of deviations from the production specifications is also necessary to be able to respond quickly to the deviations. The use of analysis methods is therefore relevant both in product development and for process control in the production system. Different methods will be relevant dependent on the purpose. The data from the measurements must be collected and analysed to contribute to more knowledge-based and data-driven decision-making to supplement and qualify personal opinions and experience in the industry. This would be an important step towards being able to respond to the increasing demand for high-variety production.

LITERATURE LIST

AACC. (2009a). Method 54-30.02. Alveograph Method for Soft and Hard Wheat Flour. Approved October 1984; re-approved November 1999. In *AACC Approved Methods of Analysis* (11th ed.). Cereals & Grains Association, St. Paul, MN, U.S.A.

AACC. (2009b). Method 54-50.01. Determination of the Water Absorption Capacity of Flours and of Physical Properties of Wheat Flour Doughs, Using the Consistograph. Approved September 1998. In *AACC Approved Methods of Analysis* (11th ed.). Cereals & Grains Association, St. Paul, MN, U.S.A.

Abuhammad, W. A., Elias, E. M., Manthey, F. A., Alamri, M. S., & Mergoum, M. (2012). A comparison of methods for assessing dough and gluten strength of durum wheat and their relationship to pasta cooking quality. *International Journal of Food Science and Technology*, *47*(12), 2561–2573.

Addo, K., Coahran, D. R., & Pomeranz, Y. (1990). A New Parameter Related to Loaf Volume Based on the First Derivative of the Alveograph Curve. *Cereal Chemistry*, *67*(1), 64–69.

Addo, K., & Pomeranz, Y. (1992). Effects of Lipids and Emulsifiers on Alveograph Characteristics. *Cereal Chemistry*, *69*(1), 6–12.

Addo, K., Pomeranz, Y., Huang, M. L., Rubenthaler, G. L., & Jeffers, H. C. (1991). Steamed bread. II. Role of protein content and strength. *Cereal Chemistry*, *68*(1), 39–42.

Addo, K., Slepak, M. T., & Akoh, C. C. (1995). Effects of Sucrose Fatty Acid Ester and Blends on Alveograph Characteristics of Wheat Flour Doughs. *Journal of Cereal Science*, *22*, 123–127.

Agyare, K. K., Addo, K., Xiong, Y. L., & Akoh, C. C. (2005). Effect of structured lipid on alveograph characteristics, baking and textural qualities of soft wheat flour. *Journal of Cereal Science*, *42*(3), 309–316.

Alava, J. M., Millar, S. J., & Salmon, S. E. (2001). The determination of wheat breadmaking performance and bread dough mixing time by NIR spectroscopy for high speed mixers. *Journal of Cereal Science*, *33*(1), 71–81.

Altuna, L., Ribotta, P. D., & Tadini, C. C. (2016). Effect of a combination of enzymes on the fundamental rheological behavior of bread dough enriched with resistant starch. *LWT - Food Science and Technology*, *73*, 267–273.

Ananingsih, V. K., Gao, J., & Zhou, W. (2013). Impact of Green Tea Extract and Fungal Alpha-Amylase on Dough Proofing and Steaming. *Food and Bioprocess Technology*, *6*(12), 3400–3411.

Andersson, R., Hämäläinen, M., & Åman, P. (1994). Predictive Modelling of the Bread-making Performance and Dough Properties of Wheat. *Journal of Cereal Science*, *20*(2), 129–138.

Aslankoohi, E., Rezaei, M. N., Vervoort, Y., Courtin, C. M., & Verstrepen, K. J. (2015). Glycerol production by fermenting yeast cells is essential for optimal bread dough fermentation. *PLoS ONE*, *10*(3), 1–13.

Baardseth, P., Næs, T., & Vogt, G. (1995). Roll-in Shortenings Effects on Danish Pastries Sensory Properties Studied by Principal Component Analysis. *Lebensmittel-Wissenschaft & Technologie*, *28*, 72–77.

Barak, S., Mudgil, D., & Khatkar, B. S. (2013). Relationship of gliadin and glutenin proteins with dough rheology, flour pasting and bread making performance of wheat varieties. *LWT - Food Science and Technology*, *51*(1), 211–217.

Barros, J. H. T., Telis, V. R. N., Taboga, S., & Franco, C. M. L. (2018). Resistant starch: effect on rheology, quality, and staling rate of white wheat bread. *Journal of Food Science and Technology*, *55*(11), 4578–4588.

Başaran, A., & Göçmen, D. (2003). The effects of low mixing temperature on dough rheology and bread properties. *European Food Research and Technology*, *217*(2), 138–142.

Bech, S., Brunoe, T. D., & Nielsen, K. (2019). Process for Enhancing the Production System Robustness with Sensor Data – a Food Manufacturer Case Study. In F. Ameri, K. Stecke, G. von Cieminski, & D. Kiritsis (Eds.), *Advances in Production Management Systems. Towards Smart Production Management Systems. APMS 2019. IFIP Advances in Information and Communication Technology* (Vol. 567, pp. 405–412). Springer.

Bech, S., Brunoe, T. D., Nielsen, K., & Andersen, A.-L. (2019). Product and process variety management: Case study in the food industry. *Procedia CIRP*, *81*, 1065–1070.

Belton, P. S. (1999). Mini Review: On the Elasticity of Wheat Gluten. *Journal of Cereal Science*, *29*(2), 103–107.

Belton, P. S. (2005). New approaches to study the molecular basis of the mechanical properties of gluten. *Journal of Cereal Science*, *41*, 203–211.

Bennett, R., & Coppock, J. B. M. (1952). Measuring the physical characteristics of flour: A method of using the Chopin alveograph to detect the effect of flour improvers. *Journal of the Science of Food and Agriculture*, *3*, 297–307.

Bennett, R., & Coppock, J. B. M. (1956). FLOUR TESTING. I. A Comparison of the Brabender Extensograph, Chopin Alveograph and Simon Extensometer Methods of Testing Bread Flours with Particular Reference to the Effect of Various Forms of Flour Treatment. *Journal of the Science of Food and Agriculture*, *7*, 754–764.

Berland, S., & Launay, B. (1995). Rheological Properties of Wheat Flour Doughs in Steady and Dynamic Shear : Effect of Water Content and Some Additives. *Cereal Chemistry*, *72*(1), 48–52.

Besseris, G. J. (2015). Profiling multiple static and transient puff-pastry characteristics with a robust-and-intelligent processor. *Journal of Food Engineering*, *164*, 40–54.

Bettge, A., Rubenthaler, G. L., & Pomeranz, Y. (1989). Alveograph Algorithms to Predict Functional Properties of Wheat in Bread and Cookie Baking. *Cereal Chemistry*, *66*(2), 81–86.

Bloksma, A. H. (1957). A calculation of the shape of the alveograms of some rheological model substances. *Cereal Chemistry*, *34*, 126–136.

Bloksma, A. H. (1990). Rheology of the Breadmaking Process. *Cereal Foods World*, *35*(2), 228–236.

Boland, M. (2006). Mass customisation of food. *Journal of the Science of Food and Agriculture*, *86*, 7–9.

Bollaín, C., & Collar, C. (2004). Dough viscoelastic response of hydrocolloid/enzyme/surfactant blends assessed by uni- and bi-axial extension measurements. *Food Hydrocolloids*, *18*(3), 499–507.

Bordes, J., Branlard, G., Oury, F. X., Charmet, G., & Balfourier, F. (2008). Agronomic characteristics, grain quality and flour rheology of 372 bread wheats in a worldwide core collection. *Journal of Cereal Science, 48*(3), 569–579.

Bousquières, J., Deligny, C., Challois, S., & Lucas, T. (2014). Using confocal laser scanning microscopy to examine the breakdown of fat layers in laminated dough. *Food Research International*, *62*, 359–365.

Bousquières, J., Deligny, C., Riaublanc, A., & Lucas, T. (2014). CLSM study of layers in laminated dough: Roll out of layers and elastic recoil. *Journal of Cereal Science*, *60*(1), 82–91.

Branlard, G., Dardevet, M., Saccomano, R., Lagoutte, F., & Gourdon, J. (2001). Genetic diversity of wheat storage proteins and bread wheat quality. *Euphytica*, *119*, 59–67.

Butow, B. J., Gras, P. W., Haraszi, R., & Bekes, F. (2002). Effects of different salts on mixing and extension parameters on a diverse group of wheat cultivars using 2-g mixograph and extensigraph methods. *Cereal Chemistry*, *79*(6), 826–833.

Caballero, P. A., Gómez, M., & Rosell, C. M. (2007). Improvement of dough rheology, bread quality and bread shelf-life by enzymes combination. *Journal of Food Engineering*, *81*(1), 42–53.

Calderón-Domínguez, G., Farrera-Rebollo, R., Arana-Errasquín, R., & Mora-Escobedo, R. (2005). The effect of varying the mixing formula on the quality of a yeast sweet bread and also on the process conditions, as studied by surface response methodology. *International Journal of Food Science and Technology*, *40*(2), 157–164.

Calderón-Domínguez, G., Vera-Domínguez, M., Farrera-Rebollo, R., Arana-Errasquín, R., & Mora-Escobedo, R. (2004). Rheological changes of dough and bread quality prepared from a sweet dough: Effect of temperature and mixing time. *International Journal of Food Properties*, *7*(2), 165–174.

Cappelli, A., Cini, E., Guerrini, L., Masella, P., Angeloni, G., & Parenti, A. (2018). Predictive models of the rheological properties and optimal water content in doughs: An application to ancient grain flours with different degrees of refining. *Journal of Cereal Science*, *83*, 229–235.

Casutt, V., Preston, K. R., & Kilborn, R. H. (1984). Effects of Fermentation Time, Inherent Flour Strength, and Salt Level on Extensigraph Properties of Full-Formula Remix-to-Peak Processed Doughs. *Cereal Chemistry*, *61*(5), 454–459.

Cauvain, S. P. (2009). The relevance of testing to the manufacture of bread and fermented products. In S. P. Cauvain & L. Young (Eds.), *The ICC handbook of cereals, flour, dough & product testing: Methods and applications* (1st ed., pp. 125–156). DEStech Publications.

Cauvain, S. P. (2015). *Technology of Breadmaking* (3rd ed.). Springer.

Cauvain, S. P., & Young, L. (Eds.). (2009). *The ICC handbook of cereals, flour, dough & product testing: Methods and applications* (1st ed.). DEStech Publications.

Chakrabarti-Bell, S., Bergström, J. S., Lindskog, E., & Sridhar, T. (2010). Computational modeling of dough sheeting and physical interpretation of the non-linear rheological behavior of wheat flour dough. *Journal of Food Engineering*, *100*(2), 278–288.

Chakrabarti-Bell, S., Patel, M. J., Ng, J., & Hawkins, W. E. (2017). On the use of low protein flours and 'smart' sheeting lines for making bakery products. *Journal of Food Engineering*, *209*, 36–44.

Charalambides, M. N., Wanigasooriya, L., Williams, J. G., & Chakrabarti, S. (2002). Biaxial deformation of dough using the bubble inflation technique. I. Experimental. *Rheologica Acta*, *41*, 532–540.

Charalambides, M. N., Wanigasooriya, L., Williams, J. G., Goh, S. M., & Chakrabarti, S. (2006). Large deformation extensional rheology of bread dough. *Rheologica Acta*, *46*, 239–248.

Chin, N. L., & Campbell, G. M. (2005a). Dough aeration and rheology: Part 1. Effects of mixing speed and headspace pressure on mechanical development of bread dough. *Journal of the Science of Food and Agriculture*, *85*(13), 2184–2193.

Chin, N. L., & Campbell, G. M. (2005b). Dough aeration and rheology: Part 2. Effects of flour type, mixing speed and total work input on aeration and rheology of bread dough. *Journal of the Science of Food and Agriculture*, *85*(13), 2194–2202.

Chin, N. L., Martin, P. J., & Campbell, G. M. (2005). Dough aeration and rheology: Part 3. Effect of the presence of gas bubbles in bread dough on measured bulk rheology and work input rate. *Journal of the Science of Food and Agriculture*, *85*(13), 2203–2212.

Chin, N. L., Rahman, R. A., Hashim, D. M., & Kowng, S. Y. (2010). Palm oil shortening effects on baking performance of white bread. *Journal of Food Process Engineering*, *33*(3), 413–433.

Chopin, M. (1927). Determination of baking value of wheat by measure of specific energy of deformation of dough. *Cereal Chemistry*, *4*(1), 1–13.

Chopin Technologies. (2016). *Alveolab - User's manual 12/2016*.

Conde-Petit, B., & Escher, F. (1995). Complexation induced changes of rheological properties of starch systems at different moisture levels. *Journal of Rheology*, *39*(6), 1497–1518.

de la Horra, A. E., Steffolani, M. E., Barrera, G. N., Ribotta, P. D., & León, A. E. (2015). Yeast-leavened laminated salty baked goods: Flour and dough properties and their relationship with product technological quality. *Food Technology and Biotechnology*, *53*(4), 446–453.

Deligny, C., Collewet, G., & Lucas, T. (2017). Quantitative MRI study of layers and bubbles in Danish pastry during the proving process. *Journal of Food Engineering*, *203*, 6–15.

Deligny, C., & Lucas, T. (2015). Effect of the number of fat layers on expansion of Danish pastry during proving and baking. *Journal of Food Engineering*, *158*, 113–120.

Dexter, J. E., Preston, K. R., Martin, D. G., & Gander, E. J. (1994). The Effects of Protein Content and Starch Damage on the Physical Dough Properties and Bread-making Quality of Canadian Durum Wheat. *Journal of Cereal Science*, *20*(2), 139–151.

Dobraszczyk, B. J. (1997). Development of a New Dough Inflation System to Evaluate Doughs. *Cereal Foods World*, *42*(7), 516–519.

Dobraszczyk, B. J. (2004a). The physics of baking: Rheological and polymer molecular structure-function relationships in breadmaking. *Journal of Non-Newtonian Fluid Mechanics*, *124*, 61–69.

Dobraszczyk, B. J. (2004b). WHEAT | Dough Rheology. In *Encyclopedia of Grain Science* (pp. 400–416). Elsevier.

Dobraszczyk, B. J., & Morgenstern, M. P. (2003). Rheology and the breadmaking process. *Journal of Cereal Science*, *38*(3), 229–245.

Dobraszczyk, B. J., & Roberts, C. A. (1994). Strain Hardening and Dough Gas Cell-wall Failure in Biaxial Extension. *Journal of Cereal Science*, *20*(3), 265–274.

Dobraszczyk, B. J., & Salmanowicz, B. P. (2008). Comparison of predictions of baking volume using large deformation rheological properties. *Journal of Cereal Science*, *47*, 292–301.

Dobraszczyk, B. J., Smewing, J., Albertini, M., Maesmans, G., & Schofield, J. D. (2003). Extensional rheology and stability of gas cell walls in bread doughs at elevated temperatures in relation to breadmaking performance. *Cereal Chemistry*, *80*(2), 218–224.

Dong, W., & Hoseney, R. C. (1995). Effects of Certain Breadmaking Oxidants and

Reducing Agents on Dough Rheological Properties. *Cereal Chemistry*, *72*(1), 58–64.

Dowell, F. E., Maghirang, E. B., Pierce, R. O., Lookhart, G. L., Bean, S. R., Xie, F., Caley, M. S., Wilson, J. D., Seabourn, B. W., Ram, M. S., Park, S. H., & Chung, O. K. (2008). Relationship of Bread Quality to Kernel, Flour, and Dough Properties. *Cereal Chemistry*, *85*(1), 82–91.

Dubois, M., Dubat, A., & Launay, B. (2008). *The AlveoConsistograph Handbook* (2nd ed.). AACC International.

Duyvejonck, A. E., Lagrain, B., Dornez, E., Delcour, J. A., & Courtin, C. M. (2012). Suitability of solvent retention capacity tests to assess the cookie and bread making quality of European wheat flours. *LWT - Food Science and Technology*, *47*(1), 56–63.

Edwards, N. M., Gianibelli, M. C., McCaig, T. N., Clarke, J. M., Ames, N. P., Larroque, O. R., & Dexter, J. E. (2007). Relationships between dough strength, polymeric protein quantity and composition for diverse durum wheat genotypes. *Journal of Cereal Science*, *45*(2), 140–149.

Edwards, N. M., Preston, K. R., Paulley, F. G., Gianibelli, M. C., McCaig, T. N., Clarke, J. M., Ames, N. P., & Dexter, J. E. (2007). Hearth bread baking quality of durum wheat varying in protein composition and physical dough properties. *Journal of the Science of Food and Agriculture*, *87*, 2000–2011.

Edwards, W. P. (2007). *The science of bakery products*. Royal Society of Chemistry.

ElMaraghy, H. A., & Wiendahl, H.-P. (2009). Changeability – An Introduction. In Hoda A. ElMaraghy (Ed.), *Changeable and Reconfigurable Manufacturing Systems* (1st ed., pp. 3–24). Springer.

Every, D., Gerrard, J. A., Gilpin, M. J., Ross, M., & Newberry, M. R. (1998). Staling in starch bread: The effect of gluten additions on specific loaf volume and firming rate. *Starch/Staerke*, *50*(10), 443–446.

Fadda, C., Sanguinetti, A. M., Del Caro, A., Collar, C., & Piga, A. (2014). Bread staling: Updating the view. *Comprehensive Reviews in Food Science and Food Safety*, *13*(4), 473–492.

Farahnaky, A., & Hill, S. E. (2007). The Effect of Salt, Water and Temperature on Wheat Dough Rheology. *Journal of Texture Studies*, *38*, 499–510.

Fu, J., Mulvaney, S. J., & Cohen, C. (1997). Effect of added fat on the rheological properties of wheat flour doughs. *Cereal Chemistry*, *74*(3), 304–311.

García-Álvarez, J., Salazar, J., & Rosell, C. M. (2011). Ultrasonic study of wheat flour properties. *Ultrasonics*, *51*(2), 223–228.

Gerrard, J. A., Newberry, M. P., Ross, M., Wilson, A. J., Fayle, S. E., & Kavale, S. (2000). Pastry lift and croissant volume as affected by microbial transglutaminase. *Journal of Food Science*, *65*(2), 312–314.

Ghotra, B. S., Dyal, S. D., & Narine, S. S. (2002). Lipid shortenings: A review. *Food Research International*, *35*(10), 1015–1048.

Goesaert, H., Brijs, K., Veraverbeke, W. S., Courtin, C. M., Gebruers, K., & Delcour, J. A. (2005). Wheat flour constituents: How they impact bread quality, and how to impact their functionality. *Trends in Food Science and Technology*, *16*(1–3), 12–30.

Goesaert, H., Leman, P., Bijttebier, A., & Delcour, J. A. (2009). Antifirming effects of starch degrading enzymes in bread crumb. *Journal of Agricultural and Food Chemistry*, *57*(6), 2346–2355.

Goesaert, H., Slade, L., Levine, H., & Delcour, J. A. (2009). Amylases and bread firming - an integrated view. *Journal of Cereal Science*, *50*(3), 345–352.

Gras, P. W., Carpenter, H. C., & Anderssen, R. S. (2000). Modelling the Developmental Rheology of Wheat-Flour Dough using Extension Tests. *Journal of Cereal Science*, *31*, 1–13.

Gray, J. A., & Bemiller, J. N. (2003). Bread Staling: Molecular Basis and Control. *Comprehensive Reviews in Food Science and Food Safety*, *2*, 1–21.

Grosch, W., & Wieser, H. (1999). Redox reactions in wheat dough as affected by ascorbic acid. *Journal of Cereal Science*, *29*(1), 1–16.

Hardt, N. A., Boom, R. M., & van der Goot, A. J. (2014). Wheat dough rheology at low water contents and the influence of xylanases. *Food Research International*, *66*, 478–484.

Hay, R. L. (1993). Effect of Flour Quality Characteristics on Puff Pastry Baking Performance. *Cereal Chemistry*, *70*(4), 392–296.

Hernández-Estrada, Z. J., Rayas-Duarte, P., Figueroa, J. D. C., & Morales-Sánchez, E. (2014). Creep recovery tests to measure the effects of wheat glutenins on doughs and the relationships to rheological and breadmaking properties.

Journal of Food Engineering, *143*, 62–68.

Hlynka, I., & Barth, F. W. (1955). Chopin alveograph studies. I. Dough resistance at constant sample deformation. *Cereal Chemistry*, *32*, 463–471.

Huen, J., Börsmann, J., Matullat, I., Böhm, L., Stukenborg, F., Heitmann, M., Zannini, E., & Arendt, E. K. (2018a). Pilot scale investigation of the relationship between baked good properties and wheat flour analytical values. *European Food Research and Technology*, *244*(3), 481–490.

Huen, J., Börsmann, J., Matullat, I., Böhm, L., Stukenborg, F., Heitmann, M., Zannini, E., & Arendt, E. K. (2018b). Wheat flour quality evaluation from the baker's perspective: comparative assessment of 18 analytical methods. *European Food Research and Technology*, *244*(3), 535–545.

Indrani, D., & Venkateswara Rao, G. (2007). Rheological characteristics of wheat flour dough as influenced by ingredients of parotta. *Journal of Food Engineering*, *79*(1), 100–105.

Ingelbrecht, J. A., Verwimp, T., & Delcour, J. A. (2000). Endoxylanases in durum wheat semolina processing: Solubilization of arabinoxylans, action of endogenous inhibitors, and effects on rheological properties. *Journal of Agricultural and Food Chemistry*, *48*(6), 2017–2022.

Janssen, A. M., van Vliet, T., & Vereijken, J. M. (1996). Fundamental and empirical rheological behaviour of wheat flour doughs and comparison with bread making performance. *Journal of Cereal Science*, *23*(1), 43–54.

Jayaram, V. B., Cuyvers, S., Lagrain, B., Verstrepen, K. J., Delcour, J. A., & Courtin, C. M. (2013). Mapping of Saccharomyces cerevisiae metabolites in fermenting wheat straight-dough reveals succinic acid as pH-determining factor. *Food Chemistry*, *136*(2), 301–308.

Jayaram, V. B., Cuyvers, S., Verstrepen, K. J., Delcour, J. A., & Courtin, C. M. (2014). Succinic acid in levels produced by yeast (Saccharomyces cerevisiae) during fermentation strongly impacts wheat bread dough properties. *Food Chemistry*, *151*, 421–428.

Jayaram, V. B., Rezaei, M. N., Cuyvers, S., Verstrepen, K. J., Delcour, J. A., & Courtin, C. M. (2014). Ethanol at levels produced by Saccharomyces cerevisiae during wheat dough fermentation has a strong impact on dough properties. *Journal of Agricultural and Food Chemistry*, *62*(38), 9326–9335.

Jekle, M., & Becker, T. (2011). Dough microstructure: Novel analysis by quantification using confocal laser scanning microscopy. *Food Research International*, *44*(4), 984–991.

Jekle, M., & Becker, T. (2012). Effects of Acidification, Sodium Chloride, and Moisture Levels on Wheat Dough: I. Modeling of Rheological and Microstructural Properties. *Food Biophysics*, *7*(3), 190–199.

Joye, I. J., Lagrain, B., & Delcour, J. A. (2009). Use of chemical redox agents and exogenous enzymes to modify the protein network during breadmaking - A review. *Journal of Cereal Science*, *50*(1), 11–21.

Kaddour, A. A., & Cuq, B. (2011). Dynamic NIR Spectroscopy to Monitor Bread Dough Mixing - A Short Review. *American Journal of Food Technology*, *6*(3), 173–185.

Khattak, S., D'Appolonia, B. L., & Banasik, O. J. (1974). Use of the alveograph for quality evaluation of hard red spring wheat. *Cereal Chemistry*, *51*, 355–363.

Kieffer, R., Kim, J. J., Walther, C., Laskawy, G., & Grosch, W. (1990). Influence of glutathione and cysteine on the improver effect of ascorbic acid stereoisomers. *Journal of Cereal Science*, *11*(2), 143–152.

Kitissou, P. (1995). Un nouveau paramètre alvéographique : l'indice d'élasticité (Ie). *Industrie Des Céréales*, *92*, 9–17.

Koehler, P. (2003). Effect of ascorbic acid in dough: Reaction of oxidized glutathione with reactive thiol groups of wheat glutelin. *Journal of Agricultural and Food Chemistry*, *51*(17), 4954–4959.

Kokawa, M., Fujita, K., Sugiyama, J., Tsuta, M., Shibata, M., Araki, T., & Nabetani, H. (2012). Quantification of the distributions of gluten, starch and air bubbles in dough at different mixing stages by fluorescence fingerprint imaging. *Journal of Cereal Science*, *55*(1), 15–21.

Kokelaar, J. J., van Vliet, T., & Prins, A. (1996). Strain Hardening Properties and Extensibility of Flour and Gluten Doughs in Relation to Breadmaking Performance. *Journal of Cereal Science*, *24*, 199–214.

Kolb, M., Blazek, P., & Streichsbier, C. (2014). Food Customisation: An Analysis of Product Configurators in the Food Industry. In *Proceedings of the 7th World Conference on Mass Customization, Personalization, and Co-Creation (MCPC 2014), Aalborg, Denmark, February 4th - 7th, 2014* (pp. 229–239).

Koren, Y. (2010). *The Global Manufacturing Revolution*. John Wiley & Sons, Inc.

Kristiawan, M., Kansou, K., & Della Valle, G. (2017). Integration of Basic Knowledge Models for the Simulation of Cereal Foods Processing and Properties. *Advances in Biochemical Engineering/Biotechnology*, *161*, 1–28.

Ktenioudaki, A., Butler, F., & Gallagher, E. (2010). The effect of different mixing processes on dough extensional rheology and baked attributes. *Journal of the Science of Food and Agriculture*, *90*(12), 2098–2104.

Ktenioudaki, A., Butler, F., & Gallagher, E. (2011). Dough characteristics of Irish wheat varieties I. Rheological properties and prediction of baking volume. *LWT - Food Science and Technology*, *44*(3), 594–601.

Kvistgaard, M., Plichta, K., & Rasmussen, O. (1993). Den danske brødindustri - Struktur, teknologi, forskningsbehov. In *MAPP working paper no 12*.

Lantmännen Unibake. (2019). *A global business, satisfying an everyday need, everywhere*. Retrieved November 30, 2020, from https://www.lantmannen-unibake.com/about-us/career/who-we-are/

Launay, B., & Buré, J. (1977). Use of the Chopin Alveographe as a Rheological Tool. II. Dough Properties in Biaxial Extension. *Cereal Chemistry*, *54*(5), 1152–1158.

Launay, B., Buré, J., & Praden, J. (1977). Use of the Chopin Alveographe as a Rheological Tool. I. Dough Deformation Measurements. *Cereal Chemistry*, *54*(5), 1042–1048.

Levine, L. (2007). Recycling and the “Age” of Dough. *Cereal Foods World*, *52*(6), 328–329.

Li, J., Hou, G. G., Chen, Z., & Gehring, K. (2013). Effects of endoxylanases, vital wheat gluten, and gum Arabic on the rheological properties, water mobility, and baking quality of whole-wheat saltine cracker dough. *Journal of Cereal Science*, *58*(3), 437–445.

Li Vigni, M., Baschieri, C., Marchetti, A., & Cocchi, M. (2013). RP-HPLC and chemometrics for wheat flour protein characterisation in an industrial bread-making process monitoring context. *Food Chemistry*, *139*, 553–562.

Li Vigni, M., Durante, C., Foca, G., Marchetti, A., Ulrici, A., & Cocchi, M. (2009). Near Infrared Spectroscopy and multivariate analysis methods for monitoring flour performance in an industrial bread-making process. *Analytica Chimica Acta*, *642*, 69–76.

Li Vigni, M., Durante, C., Foca, G., Ulrici, A., Jespersen, B. P. M., Bro, R., & Cocchi,

M. (2010). Wheat flour formulation by mixture design and multivariate study of its technological properties. *Journal of Chemometrics*, *24*, 523–533.

Lucas, I., Becker, T., & Jekle, M. (2018). Gluten polymer networks - A microstructural classification in complex systems. *Polymers*, *10*(6), 617.

Lucas, I., Petermeier, H., Becker, T., & Jekle, M. (2019). Definition of network types – Prediction of dough mechanical behaviour under shear by gluten microstructure. *Scientific Reports*, *9*(1), 4700.

Lucas, T., Collewet, G., Bousquières, J., & Deligny, C. (2018). The size of eye-shaped bubbles in Danish pastry in relation to the size of fat fragments; A reverse engineering approach of the alveolar structure. *Journal of Food Engineering*, *237*, 194–203.

Lynch, E. J., Dal Bello, F., Sheehan, E. M., Cashman, K. D., & Arendt, E. K. (2009). Fundamental studies on the reduction of salt on dough and bread characteristics. *Food Research International*, *42*(7), 885–891.

McCann, T. H., & Day, L. (2013). Effect of sodium chloride on gluten network formation, dough microstructure and rheology in relation to breadmaking. *Journal of Cereal Science*, *57*(3), 444–452.

McCann, T. H., Le Gall, M., & Day, L. (2016). Extensional dough rheology - Impact of flour composition and extension speed. *Journal of Cereal Science*, *69*, 228–237.

McGill, E. A. (1975). Puff pastry production. *Bakers Digest*, *49*, 28–38.

McIntosh, R. I., Matthews, J., Mullineux, G., & Medland, A. J. (2010). Late customisation: Issues of mass customisation in the food industry. *International Journal of Production Research*, *48*(6), 1557–1574.

Meerts, M., Cardinaels, R., Oosterlinck, F., Courtin, C. M., & Moldenaers, P. (2017). The Impact of Water Content and Mixing Time on the Linear and Non-Linear Rheology of Wheat Flour Dough. *Food Biophysics*, *12*, 151–163.

Meerts, M., Ramirez Cervera, A., Struyf, N., Cardinaels, R., Courtin, C. M., & Moldenaers, P. (2018). The effects of yeast metabolites on the rheological behaviour of the dough matrix in fermented wheat flour dough. *Journal of Cereal Science*, *82*, 183–189.

Meerts, M., Vaes, D., Botteldoorn, S., Courtin, C. M., Cardinaels, R., & Moldenaers, P. (2018). The time-dependent rheology of fermenting wheat flour dough:

effects of salt and sugar. *Rheologica Acta*, *57*(12), 813–827.

Mehfooz, T., Mohsin Ali, T., Arif, S., & Hasnain, A. (2018). Effect of barley husk addition on rheological, textural, thermal and sensory characteristics of traditional flat bread (chapatti). *Journal of Cereal Science*, *79*, 376–382.

Mehta, K. L., Scanlon, M. G., Sapirstein, H. D., & Page, J. H. (2009). Ultrasonic Investigation of the Effect of Vegetable Shortening and Mixing Time on the Mechanical Properties of Bread Dough. *Journal of Food Science*, *74*(9), E455–E461.

Morren, S., Van Dyck, T., Mathijs, F., Luca, S., Cardinaels, R., Moldenaers, P., De Ketelaere, B., & Claes, J. (2015). Applicability of the foodtexture puff device for rheological characterization of viscous food products. *Journal of Texture Studies*, *46*(2), 94–104.

Oliver, J. R., & Allen, H. M. (1992). The Prediction of Bread Baking Performance Using the Farinograph and Extensograph. *Journal of Cereal Science*, *15*(1), 79–89.

Ooms, N., & Delcour, J. A. (2019). How to impact gluten protein network formation during wheat flour dough making. *Current Opinion in Food Science*, *25*, 88–97.

Ooms, N., Jansens, K. J. A., Pareyt, B., Reyniers, S., Brijs, K., & Delcour, J. A. (2018). The impact of disulfide bond dynamics in wheat gluten protein on the development of fermented pastry crumb. *Food Chemistry*, *242*, 68–74.

Ooms, N., Pareyt, B., Brijs, K., & Delcour, J. A. (2016). Ingredient Functionality in Multilayered Dough-margarine Systems and the Resultant Pastry Products: A Review. *Critical Reviews in Food Science and Nutrition*, *56*, 2101–2114.

Ooms, N., Pareyt, B., Jansens, K. J. A., Reyniers, S., Brijs, K., & Delcour, J. A. (2017). The impact of redox agents on further dough development, relaxation and elastic recoil during lamination and fermentation of multi-layered pastry dough. *Journal of Cereal Science*, *75*, 84–91.

Pareyt, B., Finnie, S. M., Putseys, J. A., & Delcour, J. A. (2011). Lipids in bread making: Sources, interactions, and impact on bread quality. *Journal of Cereal Science*, *54*(3), 266–279.

Peighambardoust, S. H., van der Goot, A. J., van Vliet, T., Hamer, R. J., & Boom, R. M. (2006). Microstructure formation and rheological behaviour of dough under simple shear flow. *Journal of Cereal Science*, *43*(2), 183–197.

Perego, P., Sordi, A., Guastalli, R., & Converti, A. (2007). Effects of changes in ingredient composition on the rheological properties of a biscuit industry dough. *International Journal of Food Science and Technology*, *42*(6), 649–657.

Pine, B. J. (1993). *Mass Customization: The New Frontier in Business Competition*. Harvard Business Review Press.

Preston, K. R., Kilborn, R. H., & Dexter, J. E. (1987). Effects of Starch Damage and Water Absorption on the Alveograph Properties of Canadian Hard Red Spring Wheats. *Canadian Institute of Food Science and Technology Journal*, *20*(2), 75–80.

Quayson, E. T., Marti, A., Bonomi, F., Atwell, W., & Seetharaman, K. (2016). Structural Modification of Gluten Proteins in Strong and Weak Wheat Dough as Affected by Mixing Temperature. *Cereal Chemistry*, *93*(2), 189–195.

Rasper, V. F., Pico, M. L., & Fulcher, R. G. (1986). Alveograph in Quality Assessment of Soft White Winter Wheat Cultivars. *Cereal Chemistry*, *63*(5), 395–400.

Renzetti, S., De Harder, R., & Jurgens, A. (2015). Puff pastry with low saturated fat contents: The role of fat and dough physical interactions in the development of a layered structure. *Journal of Food Engineering*, *170*, 24–32.

Rezaei, M. N., Jayaram, V. B., Verstrepen, K. J., & Courtin, C. M. (2016). The impact of yeast fermentation on dough matrix properties. *Journal of the Science of Food and Agriculture*, *96*(11), 3741–3748.

Rosell, C. M., & Collar, C. (2009). Effect of temperature and consistency on wheat dough performance. *International Journal of Food Science and Technology*, *44*(3), 493–502.

Rosell, C. M., Collar, C., & Haros, M. (2007). Assessment of hydrocolloid effects on the thermo-mechanical properties of wheat using the Mixolab. *Food Hydrocolloids*, *21*(3), 452–462.

Rosell, C. M., Wang, J., Aja, S., Bean, S., & Lookhart, G. (2003). Wheat flour proteins as affected by transglutaminase and glucose oxidase. *Cereal Chemistry*, *80*(1), 52–55.

Ross, K. A., Pyrak-Nolte, L. J., & Campanella, O. H. (2004). The use of ultrasound and shear oscillatory tests to characterize the effect of mixing time on the rheological properties of dough. *Food Research International*, *37*(6), 567–577.

Sahin, A. W., Zannini, E., Coffey, A., & Arendt, E. K. (2019). Sugar reduction in bakery products: Current strategies and sourdough technology as a potential novel approach. *Food Research International*, *126*, 108583.

Salazar, J., Álava, J. M., Sahi, S. S., Turó, A., Chavéz, J. A., & García, M. J. (2002). Ultrasound measurements for determining rheological properties of flour-water systems. *IEEE Ultrasonics Symposium*, *1*, 877–880.

Salimi Khorshidi, A., Hatcher, D. W., Page, J. H., & Scanlon, M. G. (2018). A novel method to assess the mechanical behavior of Asian noodles during the sheeting process. I. The effect of repeated lamination. *Food and Bioproducts Processing*, *112*, 131–136.

Salvador, A., Sanz, T., & Fiszman, S. M. (2006). Dynamic rheological characteristics of wheat flour-water doughs. Effect of adding NaCl, sucrose and yeast. *Food Hydrocolloids*, *20*(6), 780–786.

Salvador, F., de Holan, P. M., & Piller, F. (2009). Cracking the Code of Mass Customization. *MIT Sloan Management Review*, *50*(3), 71–78.

Scanlon, M. G., & Zghal, M. C. (2001). Bread properties and crumb structure. *Food Research International*, *34*(10), 841–864.

Schiedt, B., Baumann, A., Conde-Petit, B., & Vilgis, T. A. (2013). Short- and long-range interactions governing the viscoelastic properties during wheat dough and model dough development. *Journal of Texture Studies*, *44*(4), 317–332.

Schiraldi, A., & Fessas, D. (2012). The role of water in dough formation and bread quality. In S. P. Cauvain (Ed.), *Bread Making: Improving Quality* (2nd ed., pp. 352–369). Woodhead Publishing.

Schirmer, M., Zeller, J., Krause, D., Jekle, M., & Becker, T. (2014). In situ monitoring of starch gelatinization with limited water content using confocal laser scanning microscopy. *European Food Research and Technology*, *239*(2), 247–257.

Sharp, T. (2001). Technical constraints in the development of reduced-fat bakery products. *Proceedings of the Nutrition Society*, *60*(4), 489–496.

Shibata, M., Araki, T., & Sagara, Y. (2008). Development of specified protocols and methodology in the application of food kansei model for the optimal design of Danish pastry. *Food Science and Technology Research*, *14*(4), 367–376.

Singh, H., & MacRitchie, F. (2001). Application of Polymer Science to Properties of Gluten. *Journal of Cereal Science*, *33*(3), 231–243.

Sliwinski, E. L., Kolster, P., & van Vliet, T. (2004a). Large-deformation properties of wheat dough in uni- and biaxial extension. Part I. Flour dough. *Rheologica Acta, 43,* 306–320.

Sliwinski, E. L., Kolster, P., & van Vliet, T. (2004b). On the relationship between large-deformation properties of wheat flour dough and baking quality. *Journal of Cereal Science*, *39*(2), 231–245.

Song, Y., & Zheng, Q. (2007). Dynamic rheological properties of wheat flour dough and proteins. *Trends in Food Science and Technology*, *18*(3), 132–138.

Spies, R. (1990). Application of rheology in the bread industry. In H. Faridi & J. M. Faubion (Eds.), *Dough rheology and baked product texture* (1st ed., pp. 343–361). Springer.

Sroan, B. S., Bean, S. R., & MacRitchie, F. (2009). Mechanism of gas cell stabilization in bread making. I. The primary gluten-starch matrix. *Journal of Cereal Science*, *49*(1), 32–40.

Stojceska, V., & Butler, F. (2012). Investigation of reported correlation coefficients between rheological properties of the wheat bread doughs and baking performance of the corresponding wheat flours. *Trends in Food Science and Technology, 24*(1), 13–18.

Struyf, N., Van der Maelen, E., Hemdane, S., Verspreet, J., Verstrepen, K. J., & Courtin, C. M. (2017). Bread Dough and Baker's Yeast: An Uplifting Synergy. *Comprehensive Reviews in Food Science and Food Safety*, *16*(5), 850–867.

Thorvaldsson, K., & Skjoldebrand, C. (1998). Water Diffusion in Bread During Baking. *Lebensmittel-Wissenschaft & Technologie*, *31*, 658–663.

Tlapale-Valdivia, A. D., Chanona-Pérez, J., Mora-Escobedo, R., Farrera-Rebollo, R. R., Gutiérrez-López, G. F., & Calderón, G. (2010). Dough and crumb grain changes during mixing and fermentation and their relation with extension properties and bread quality of yeasted sweet dough. *International Journal of Food Science and Technology, 45*(3), 530–539.

Tronsmo, K. M., Færgestad, E. M., Schofield, J. D., & Magnus, E. M. (2003). Wheat protein quality in relation to baking performance evaluated by the Chorleywood bread process and a hearth bread baking test. *Journal of Cereal Science*, *38*(2), 205–215.

Tronsmo, K. M., Magnus, E. M., Baardseth, P., Schofield, J. D., Aamodt, A., & Færgestad, E. M. (2003). Comparison of small and large deformation rheological properties of wheat dough and gluten. *Cereal Chemistry*, *80*(5), 587–595.

Ulrici, A., Li Vigni, M., Durante, C., Foca, G., Belloni, P., Brettagna, B., De Marco, T., & Cocchi, M. (2008). At-line monitoring of the leavening process in industrial bread making by near infrared spectroscopy. *Journal of Near Infrared Spectroscopy*, *16*(3), 223–231.

van Bockstaele, F., Leyn, I. De, Eeckhout, M., & Dewettinck, K. (2008). Rheological Properties of Wheat Flour Dough and Their Relationship with Bread Volume. II. Dynamic Oscillation Measurements. *Cereal Chemistry*, *85*(6), 762–768.

van der Sman, R. G. M., & van der Goot, A. J. (2009). The science of food structuring. *Soft Matter*, *5*, 501–510.

Van Steertegem, B., Pareyt, B., Brijs, K., & Delcour, J. A. (2013). The effects of fresh eggs, egg white, and egg yolk, separately and in combination with salt, on Mixogram properties. *Cereal Chemistry*, *90*(3), 269–272.

van Vliet, T., Janssen, A. M., Bloksma, A. H., & Walstra, P. (1992). Strain hardening of dough as a requirement for gas retention. *Journal of Texture Studies*, *23*, 439–460.

Vanin, F. M., Lucas, T., Trystram, G., & Michon, C. (2018). Biaxial extensional viscosity in wheat flour dough during baking. *Journal of Food Engineering*, *236*, 29–35.

Vázquez, D., Berger, A. G., Cuniberti, M., Bainotti, C., de Miranda, M. Z., Scheeren, P. L., Jobet, C., Zúñiga, J., Cabrera, G., Verges, R., & Peña, R. J. (2012). Influence of cultivar and environment on quality of Latin American wheats. *Journal of Cereal Science*, *56*(2), 196–203.

Verheyen, C., Albrecht, A., Herrmann, J., Strobl, M., Jekle, M., & Becker, T. (2015). The contribution of glutathione to the destabilizing effect of yeast on wheat dough. *Food Chemistry*, *173*, 243–249.

Verheyen, C., Jekle, M., & Becker, T. (2014). Effects of Saccharomyces cerevisiae on the structural kinetics of wheat dough during fermentation. *LWT - Food Science and Technology*, *58*(1), 194–202.

Wang, F. C., & Sun, X. S. (2002). Creep-recovery of wheat flour doughs and relationship to other physical dough tests and breadmaking performance. *Cereal Chemistry*, *79*(4), 567–571.

Wang, J., Rosell, C. M., & Benedito de Barber, C. (2002). Effect of the addition of different fibres on wheat dough performance and bread quality. *Food Chemistry*, *79*(2), 221–226.

Wang, Y., Ma, H.-S., Yang, J.-H., & Wang, K.-S. (2017). Industry 4.0: a way from mass customization to mass personalization production. *Advances in Manufacturing*, *5*(4), 311–320.

Weegels, P. L., de Groot, A. M. G., Verhoek, J. A., & Hamer, R. J. (1994). Effects on Gluten of Heating at Different Moisture Contents. II. Changes in Physico-Chemical Properties and Secondary Structure. *Journal of Cereal Science*, *19*(1), 39–47.

Wehrle, K., Grau, H., & Arendt, E. K. (1997). Effects of lactic acid, acetic acid, and table salt on fundamental rheological properties of wheat dough. *Cereal Chemistry*, *74*(6), 739–744.

Wesley, I. J., Larsen, N., Osborne, B. G., & Skerritt, J. H. (1998). Non-invasive Monitoring of Dough Mixing by Near Infrared Spectroscopy. *Journal of Cereal Science*, *27*, 61–69.

Wickramarachchi, K. S., Sissons, M. J., & Cauvain, S. P. (2015). Puff pastry and trends in fat reduction: An update. *International Journal of Food Science and Technology*, *50*(5), 1065–1075.

Wieser, H. (2007). Chemistry of gluten proteins. *Food Microbiology*, *24*(2), 115–119.

Zanetti, S., Winzeler, M., Feuillet, C., Keller, B., & Messmer, M. (2001). Genetic analysis of bread-making quality in wheat and spelt. *Plant Breeding*, *120*(1), 13–19.

APPENDED PAPERS

ISSN (online): 2446-1636
ISBN (online): 978-87-7210-870-4

AALBORG UNIVERSITY PRESS